Prospects for Low-x Physics at RHIC

This is not a talk on an electron-ion collider. This is a talk about how improved experimental instrumentation at RHIC can extend kinematic reach to low-x. Such improvements have impact on measurements sensitive to high gluon densities in heavy-ion physics and on determining the polarization of gluons to low-x for spin physics.

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Brookhaven National Laboratory
POETIC-7 Workshop, Temple University
15 November 2016

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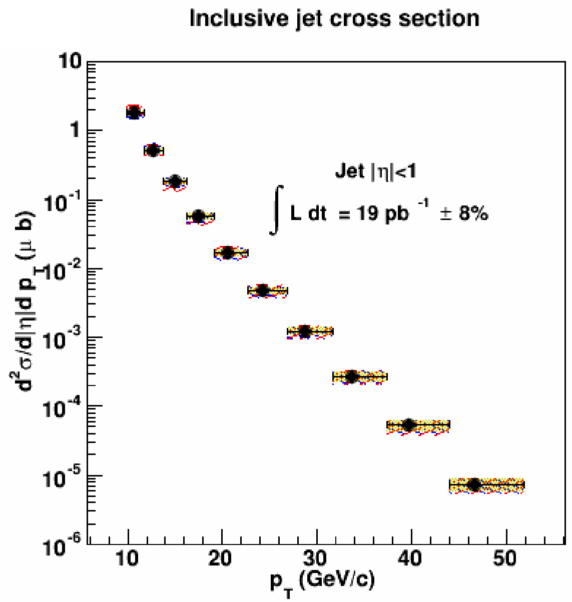
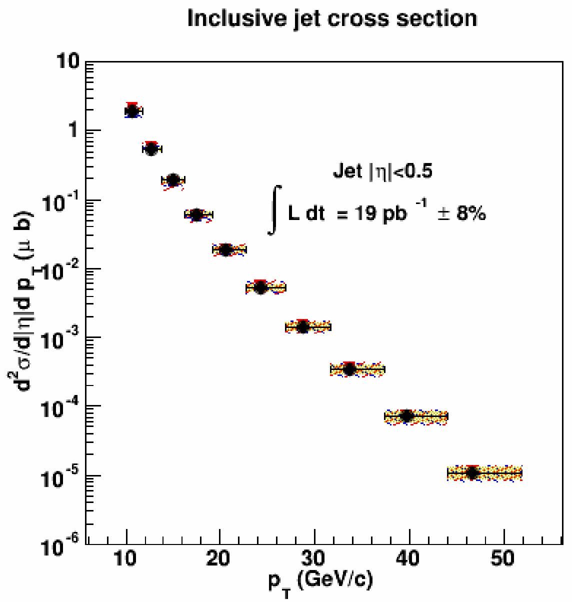
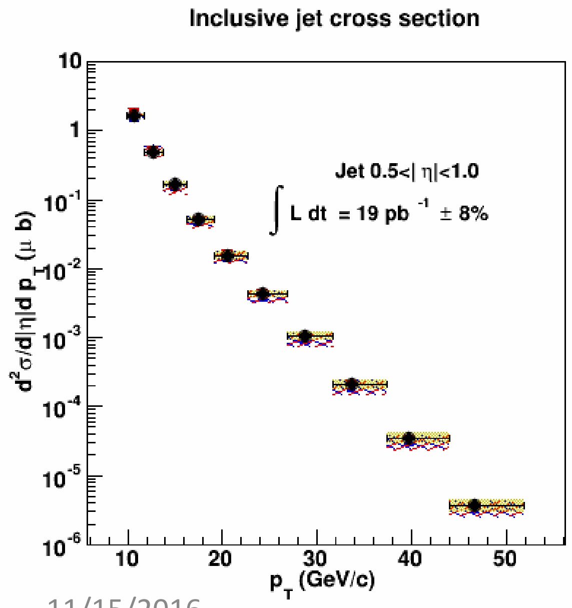
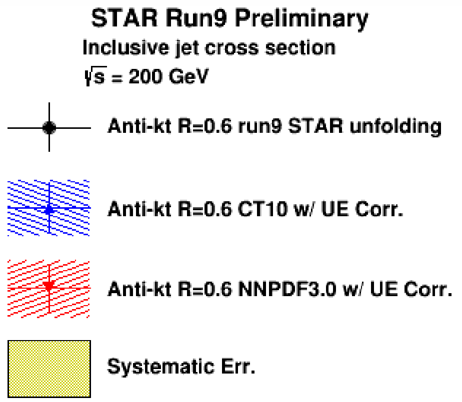
p+p→jets, √s=200 GeV







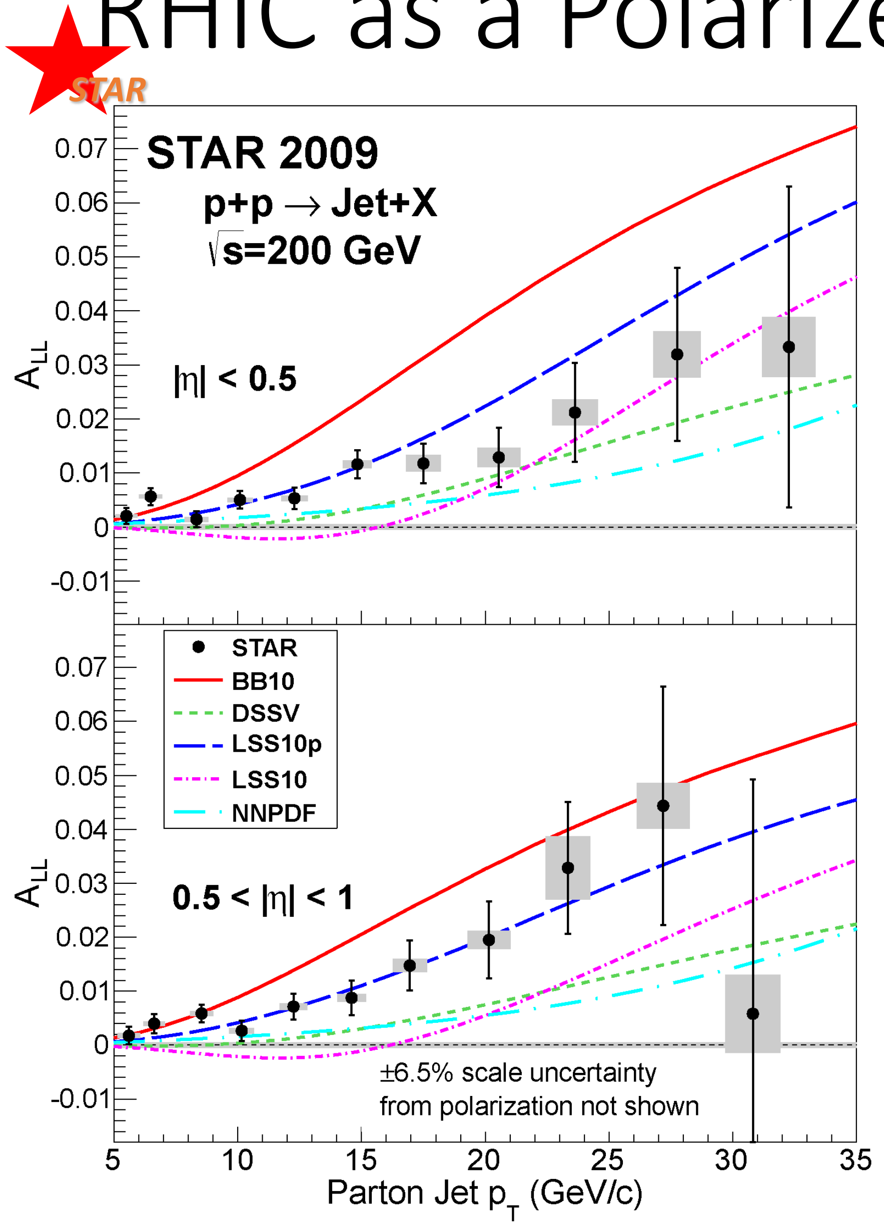


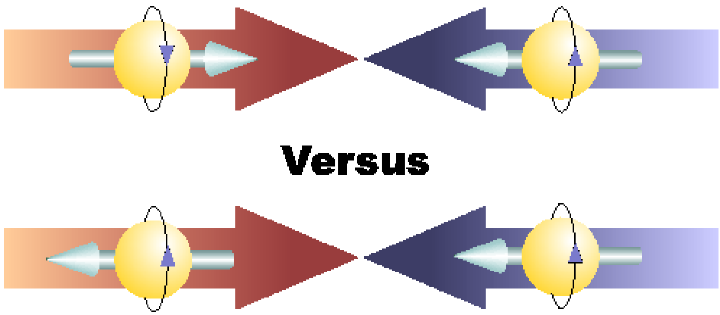
arXiv:1506.06314

RHIC and midrapidity

- Sophisticated mid-rapidity detectors have delivered a wealth of information about QCD in p+p, p+A, and A+A collisions
- Jet cross sections in p+p collisions at √s=200 GeV compare well to global analyses of parton distribution functions [arXiv:1506.06314]
- Many other examples can be provided

RHIC as a Polarized Collider





$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

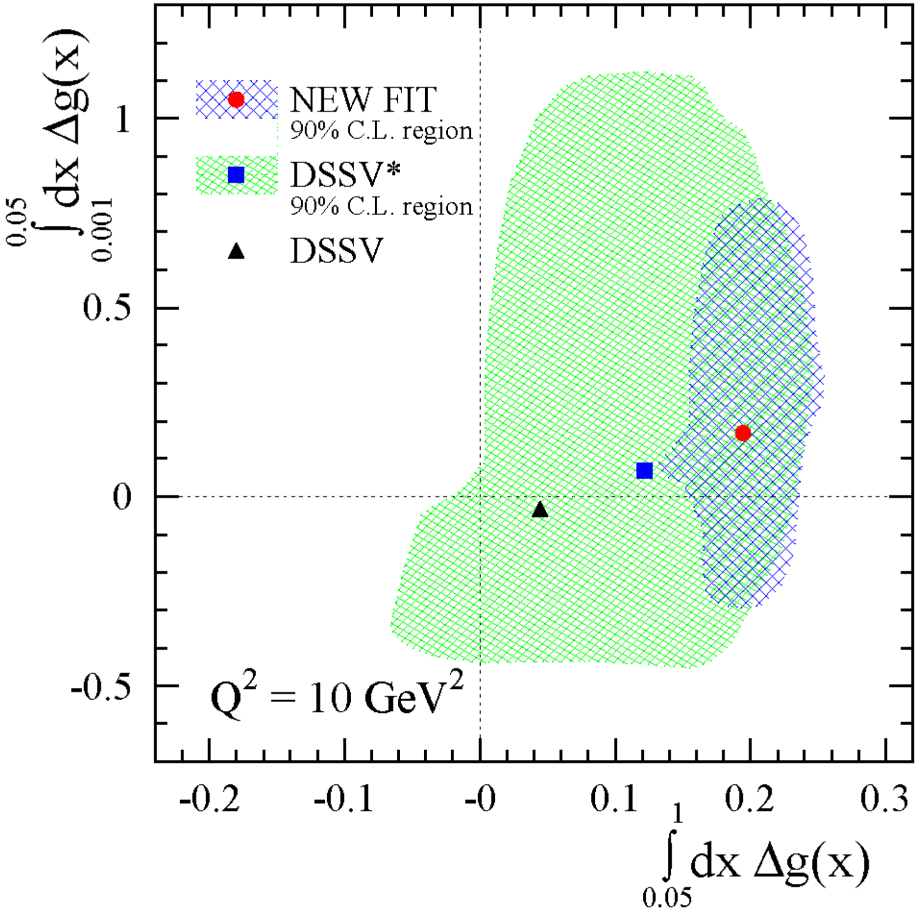
- Helicity asymmetry for inclusive jet production at midrapidity is measured as a function of p_T.
- Measurements are sensitive to $\langle x \rangle \sim 2p_T/\sqrt{s}$

arXiv:1405.5134
PRL 115 (2015) 092002

Gluon Polarization

Large Uncertainty in Low-x Gluon Contribution to Proton Spin

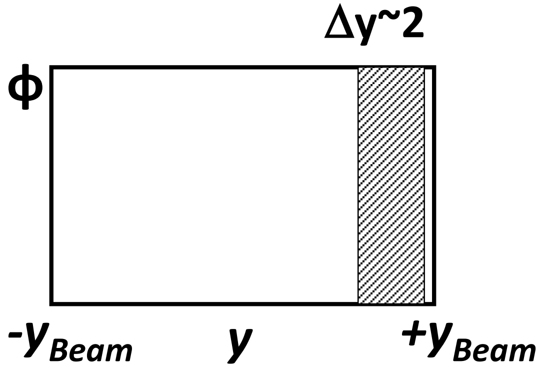
de Florian, Sassot, Stratmann, Vogelsang
PRL 113 (2014) 012001 / arXiv:1404.4293



- Spin decomposition of proton: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$ [arXiv:1309.4235] in terms of quark and gluon spin and orbital angular momentum
- In measured range of x [midrapidity], global analysis [arXiv:1404.4293] of world data determines $\Delta G=0.20\pm0.06$ for $x>0.05$ at $Q^2=10$ GeV^2
- For x<0.05, little is known experimentally until an EIC
- RHIC can still make measurements sensitive to gluon polarization down to $x\sim10^{-3}$ with forward instrumentation

Forward Particle Production

- In this talk, forward means when the observed particle Feynman-x ($x_F=2p_z/\sqrt{s}$) scaling variable is larger than 0.1
- In general, sufficient p_T is required so that pQCD is applicable. Consequently, forward is further defined to require sufficient p_T [which looks to be ~2 GeV/c for inclusive π^0 production]
- RHIC interaction regions have uniquely large length for a collider, when scaled by $\sqrt{s}$. This interaction length does permit space for forward instrumentation



	Free Space (m)	√s (GeV)	Ratio (L/√s)
Tevatron	13	1600	0.0081
LHC	38	13000	0.0029
RHIC	16	500	0.032
	16	200	0.080

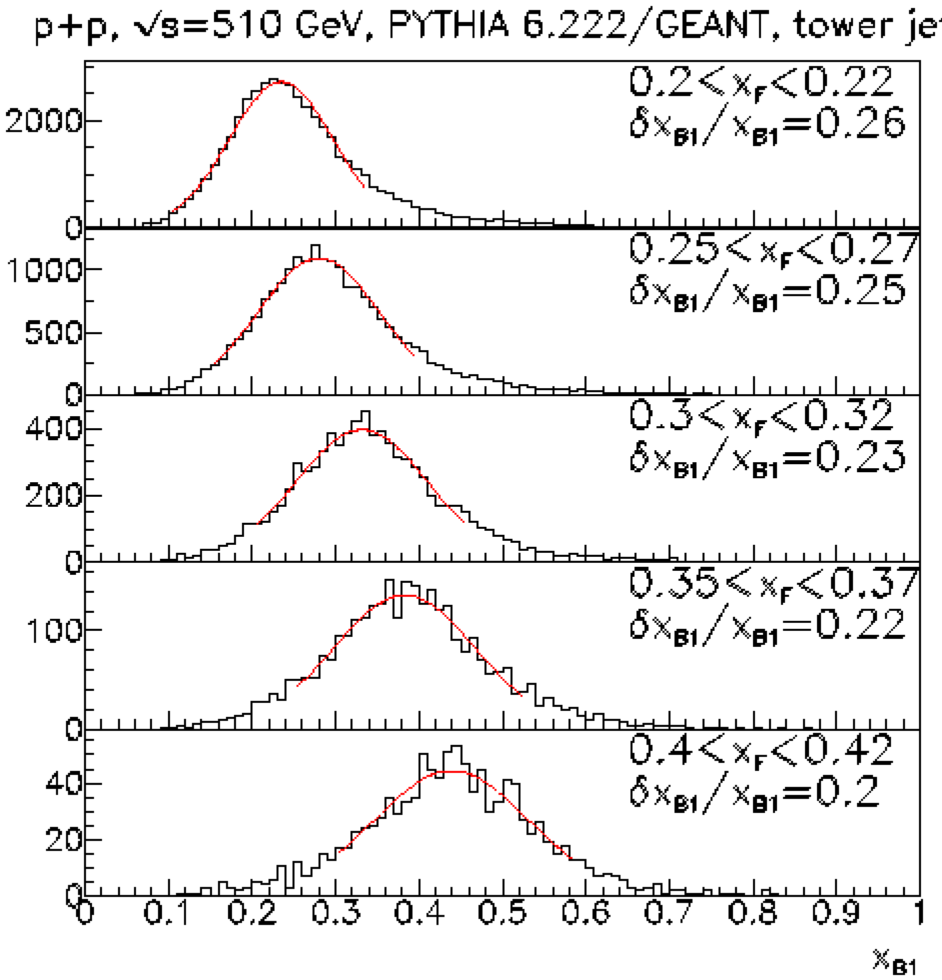
Consider the separation in x-y plane ($d_{\gamma\gamma}$) of a pair of photons from the decay $M\rightarrow\gamma\gamma$, when the plane is L from where M (mass m_M) is produced:

$$d_{\gamma\gamma}^{min} = \frac{L}{\sqrt{s}}\frac{4m_M}{x_F}$$

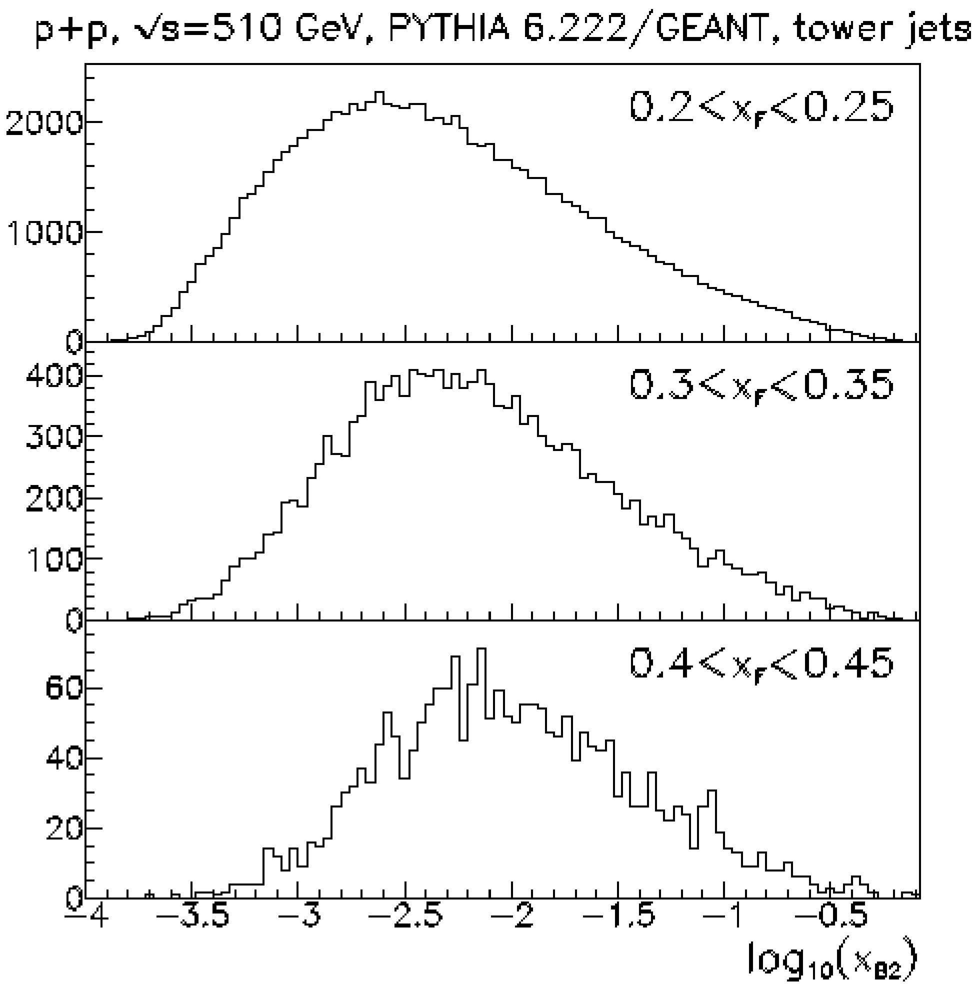
$\Rightarrow$ Large $L/\sqrt{s}$ enables reconstruction of light mesons to large x_F at large $\sqrt{s}$

Why is large x_F useful?

For inclusive production via hard scattering (2→2 processes), $x_F \sim x_1 - x_2$, where x_1 is the Bjorken x of the parton from the hadron heading towards the apparatus and x_2 is the Bjorken x of the parton from the other colliding hadron. In general, forward particle production probes these x values at "low scale" (as set by p_T). Distributions are for inclusive forward jets.

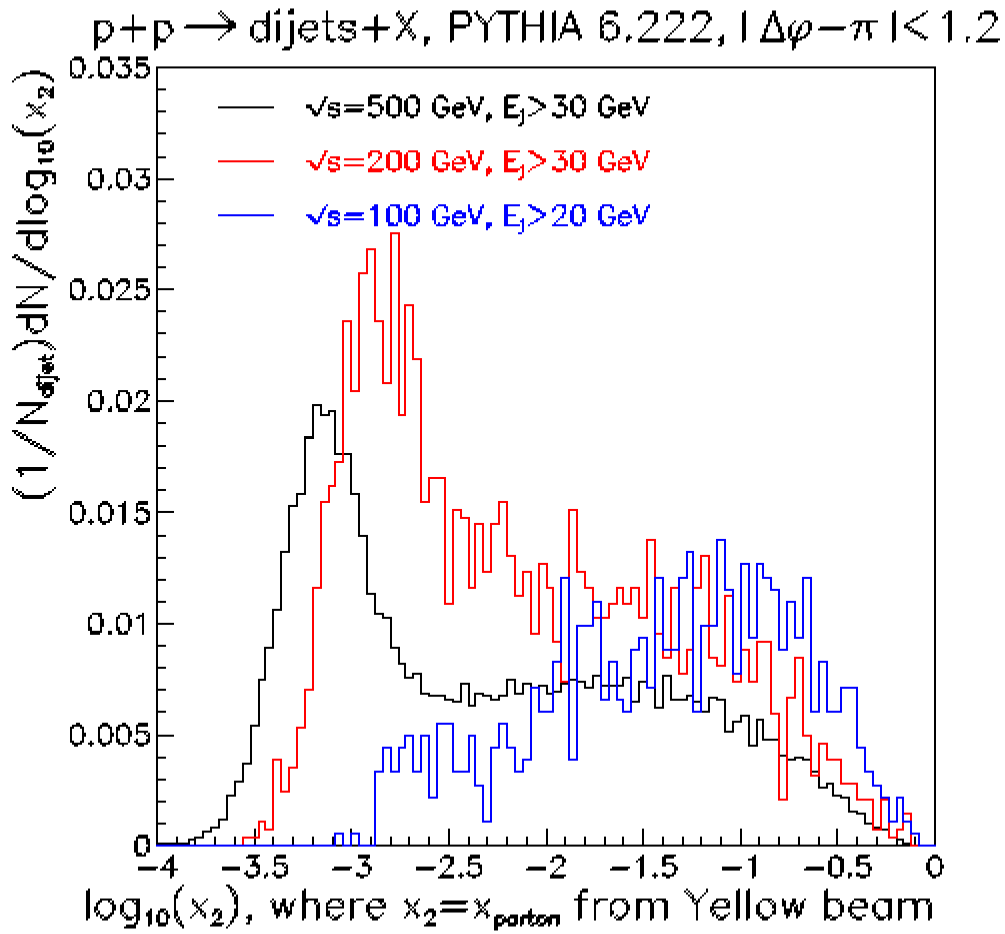


Valence-like quarks for x_F>0.1



x_2 is broad, but extends to very low x (~few × 10^{-4}).
Forward dijets can select low x (see below)

Forward Dijets



Reconstruction of >1 jet in the forward direction can emphasize hard-scattering contributions from lox-x gluons

Examples of why this is important are

- Extending probes of gluon polarization to low-x by measurement of longitudinal double-spin asymmetries
- Sensitivity to low-x gluons in heavy ions

Proposals for Forward Upgrades at RHIC

- Forward sPHENIX – see http://www.phenix.bnl.gov/phenix/WWW/publish/dave/sPHENIX/pp_pA_whitepaper.pdf

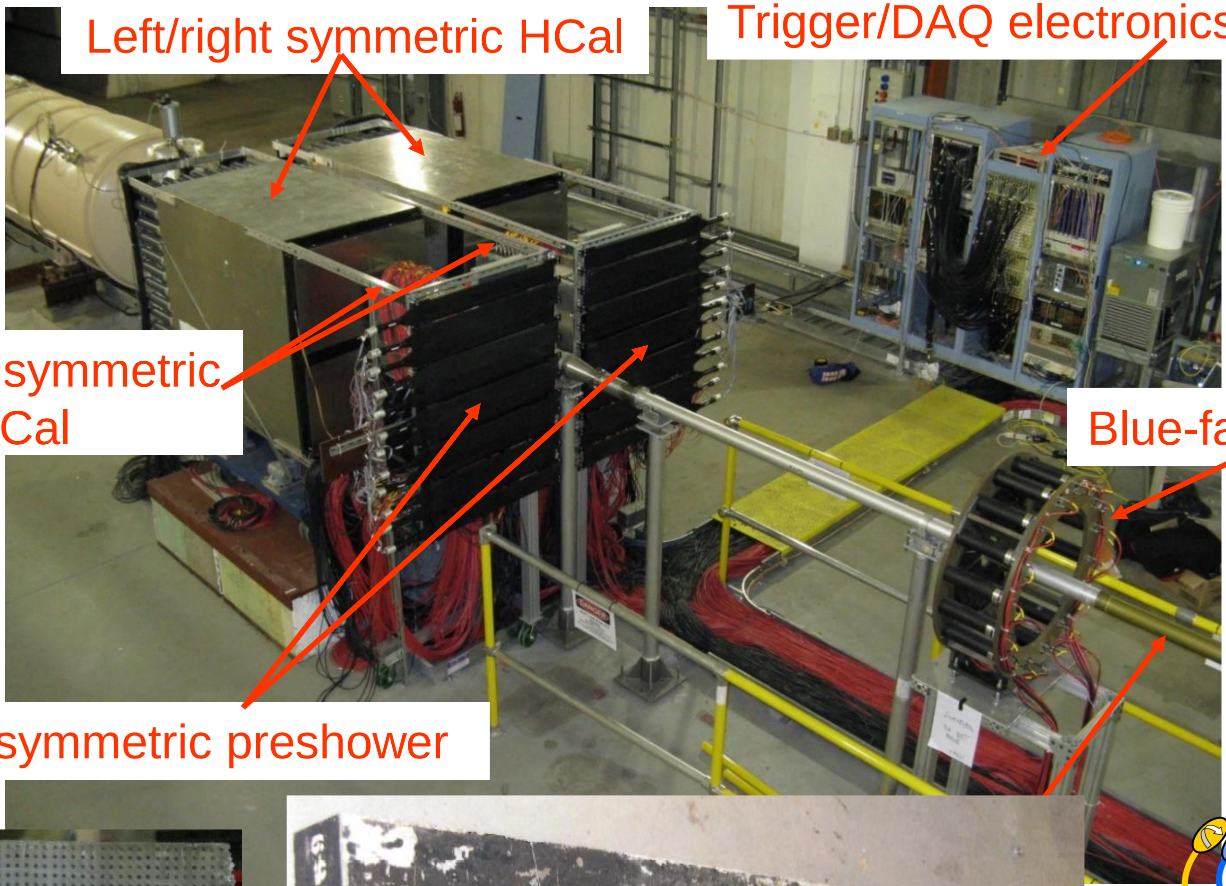
- STAR Forward Detector Update – see arXiv:1602.03922 and E. Aschenauer talk in session 4B

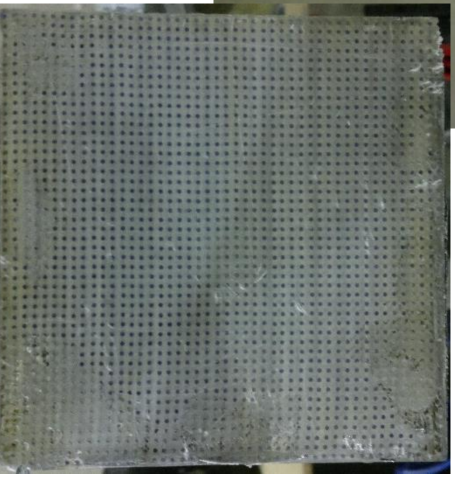
- Forward Calorimeter at STAR – described below following Outline
    - Prior use of FCal at RHIC – forward jet and dijet cross sections
    - Tests of FCal at STAR and with test beam at FermiLab
    - Proposal for installation

Prior Experience with Forward Calorimetry

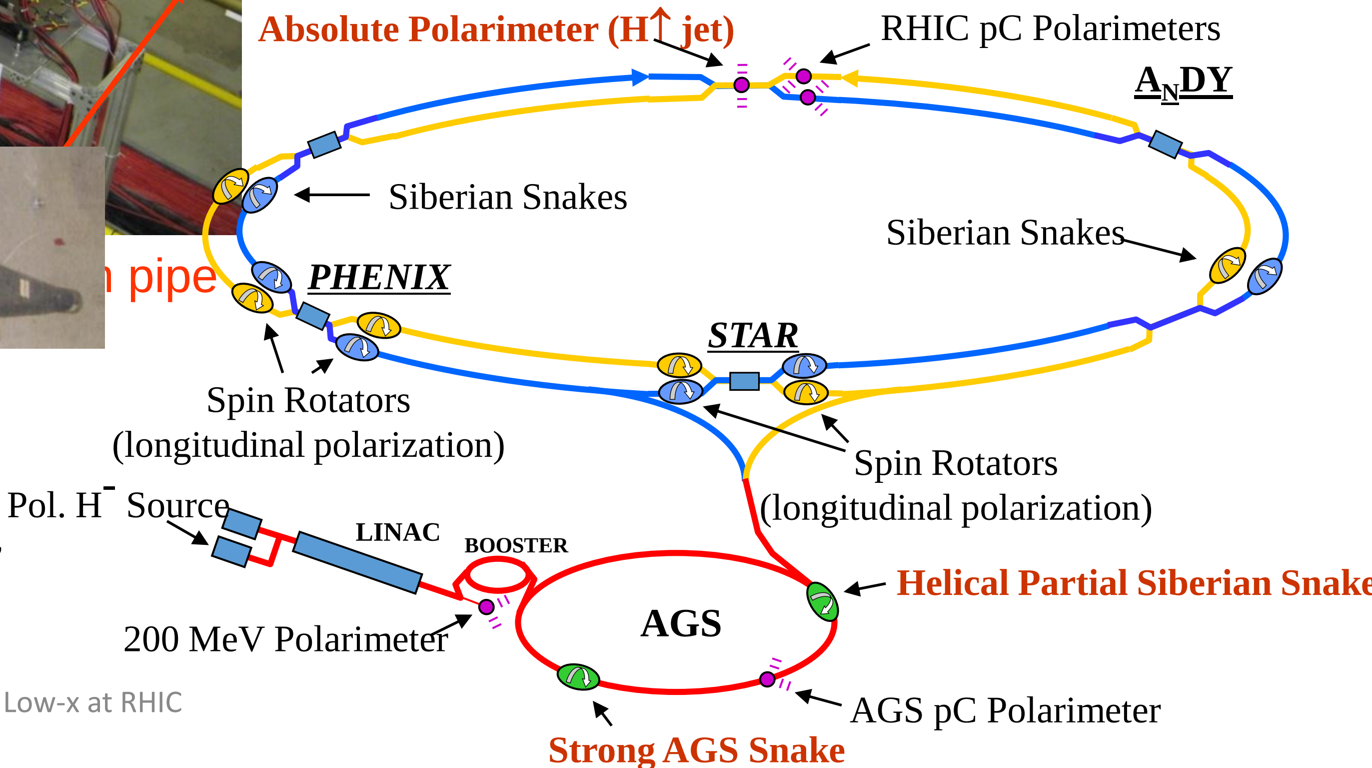
A_NDY Setup at IP2 for 2011 RHIC Run

- This was a stage-1 test that could not have worked for forward DY
- The stage-1 test did measure forward jets
- There were not further stages





117-cm long x $(10\text{cm})^2$ spaghetti calorimeter (SPACAL) built by AGS-E864 collaboration [Armstrong et al., NIM A406 (1998) 227.]



A_NDY Setup at IP2 for 2011 RHIC Run

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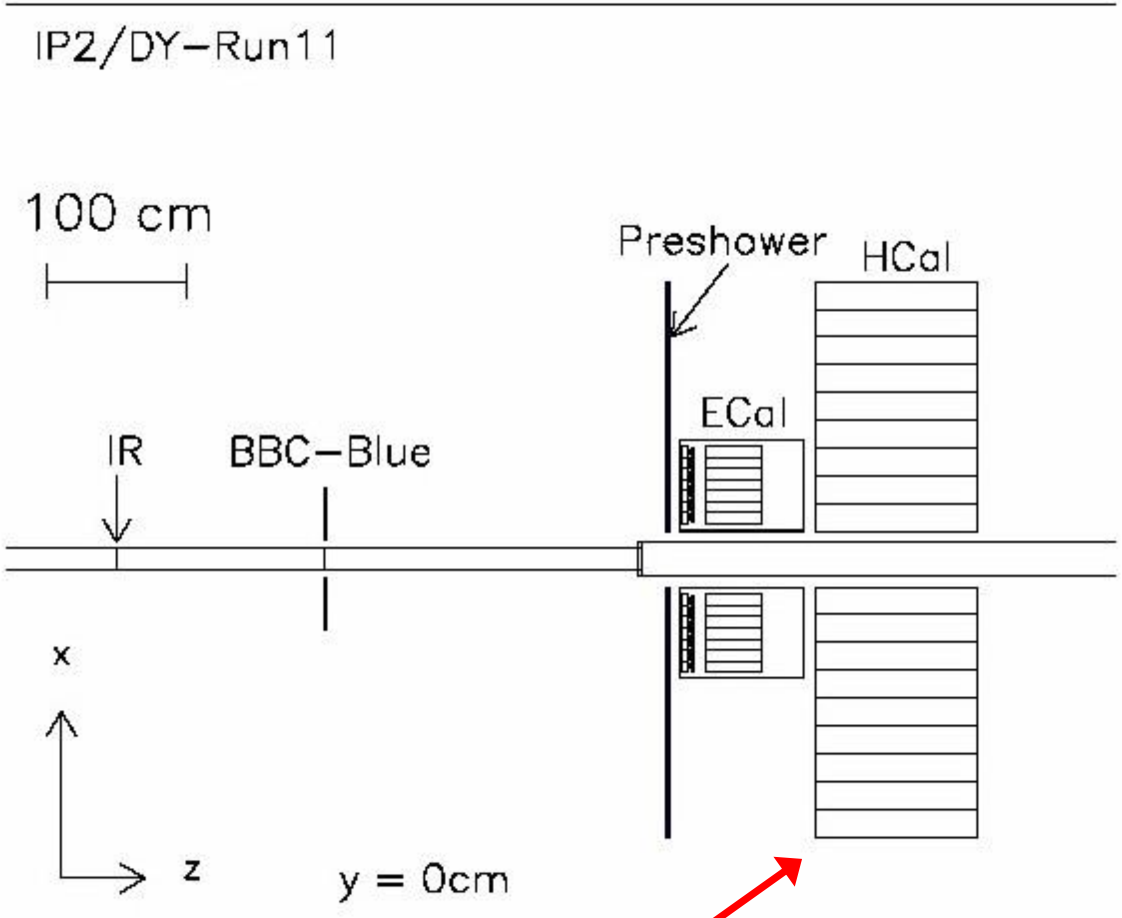

2m x 1.2m forward calorimeter
236 x $(10cm)^2$ x 117-cm cells

- Beam-beam counter (BBC) for minimum-bias trigger and luminosity measurement (from PHOBOS [NIM A474 (2001) 38])
- Zero-degree calorimeter and shower maximum detector for luminosity measurement and local polarimetry (ZDC/ZDC-SMD, not shown)
- Hadron calorimeter (HCal) are L/R symmetric modules of 9x12 lead-scintilating fiber cells, $(10cm)^2$x117cm (from AGS-E864 [NIM406(1998)227])
- Small ECal - 7x7 matrices of lead glass cells, $(4cm)^2$x40cm (loaned from BigCal at JLab)
- Preshower detector - two planes, 2.5 & 10 cm
- In 2012, modular calorimeters were replaced by an annular calorimeter with $(20cm)^2$ hole for beams

Calibrations-I

Electromagnetic Response / Calibrate via $\pi^0 \rightarrow \gamma\gamma$

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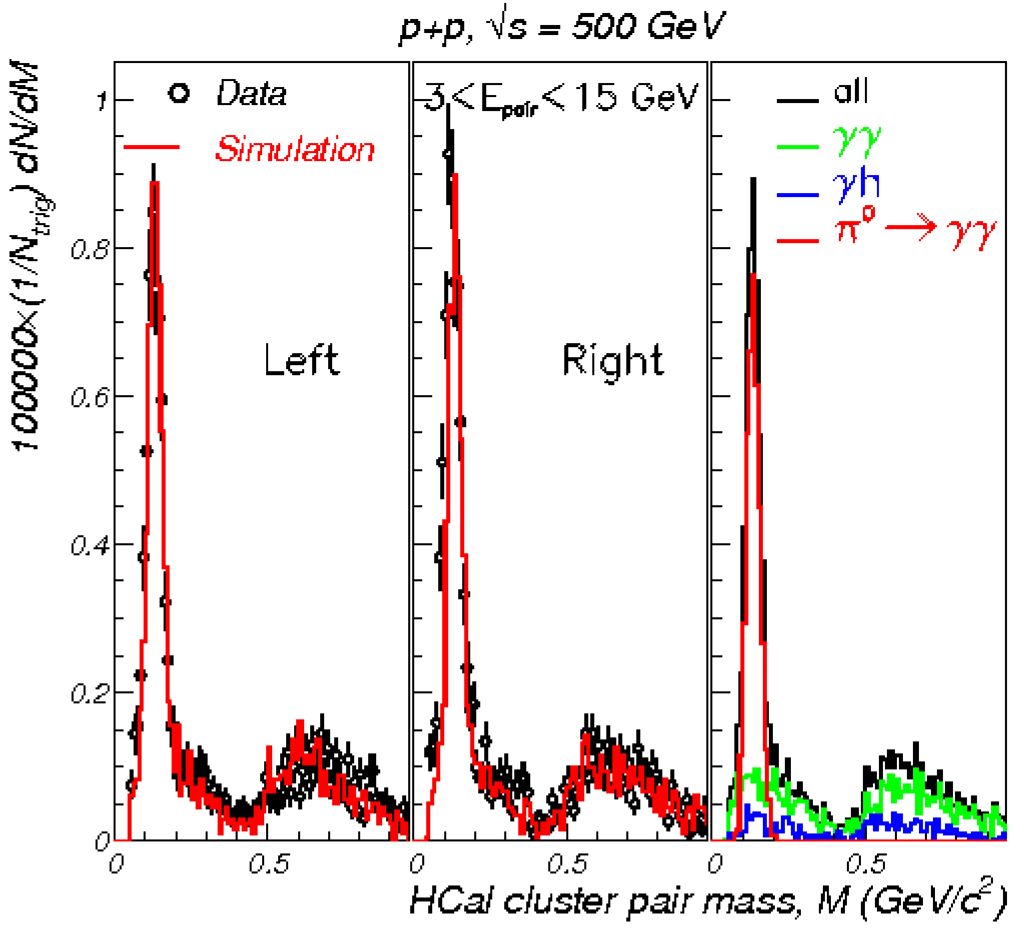

- Cosmic-ray muons were used to adjust relative gains in advance of collisions (see backup)
- The primary determination of the energy scale was from reconstruction of $\pi^0 \rightarrow \gamma\gamma$ from single-tower cluster pairs. The maximum energy for this calibration was limited by photon merging into the coarse (10 cm)^2 towers. [See below for pixelization results from this same calorimeter]
- Full PYTHIA/GEANT simulation agrees with data, for both the pair-mass resolution of the calorimeter, as well as the neutral pion reconstruction efficiency.
- Subsequent test-beam studies at FNAL [T1064] are consistent with an excellent response of this calorimeter to incident photons and electrons.

Calibrations-II

arXiv:1308.4705

Hadronic Reponse

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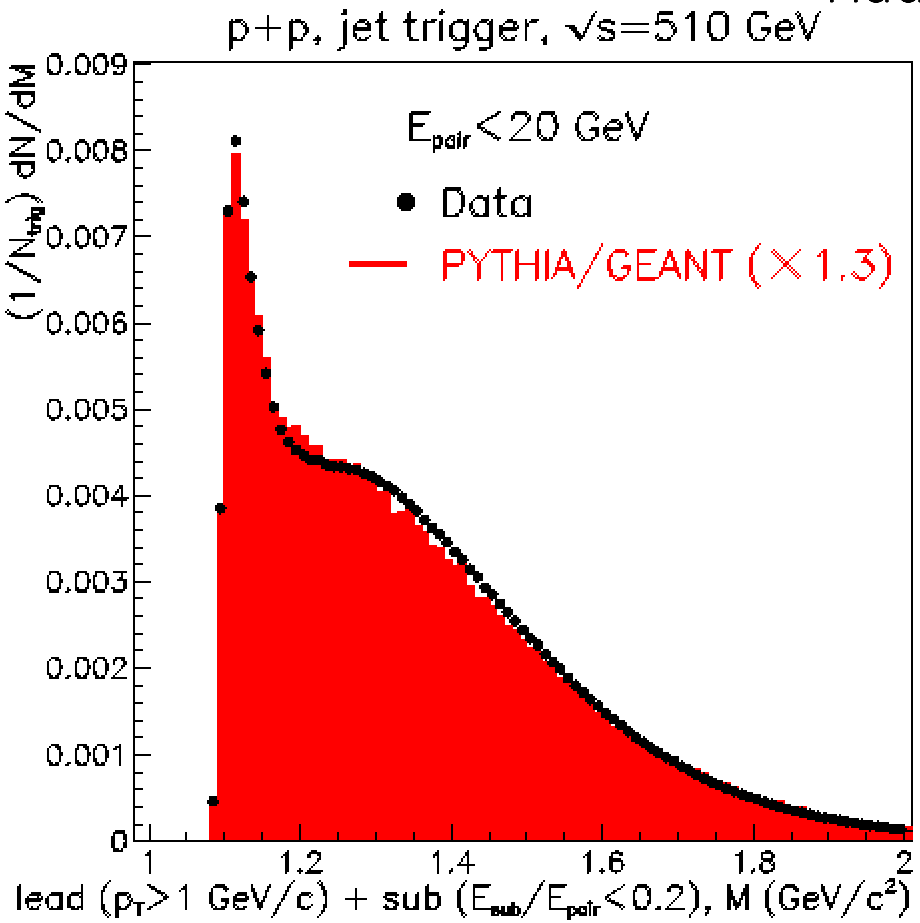
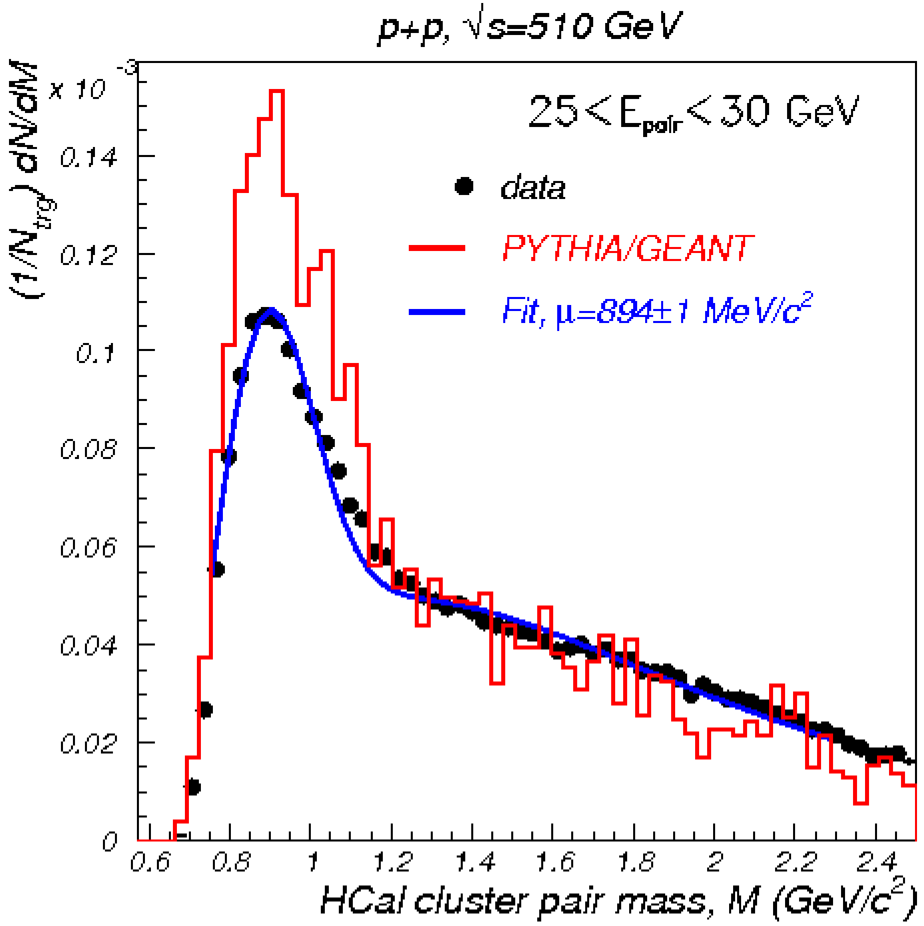
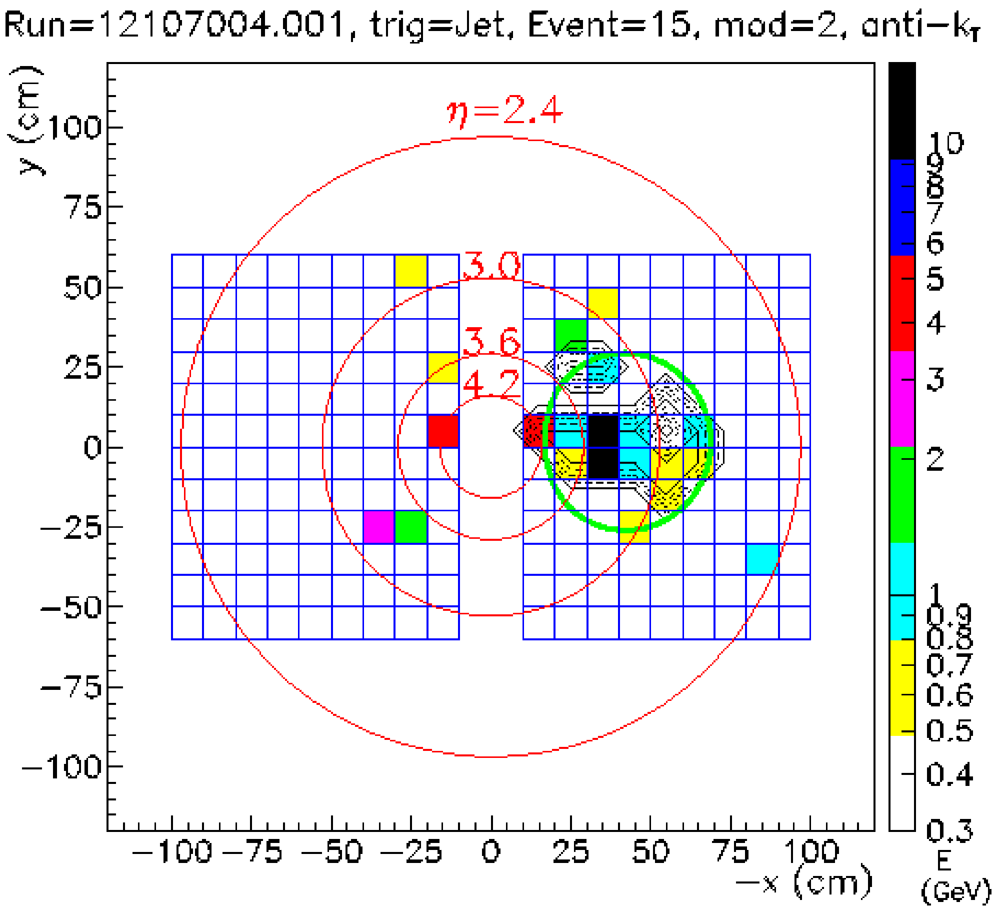




- Use BBC detector to tag HCal clusters made by incident charged hadrons. Mass assignments are then made.
- Tagged cluster-pair mass distributions are consistent with $\Lambda \rightarrow \pi^- p$ (left) and K*(892) $\rightarrow \pi^+ K^-$ (right) and charge conjugates
- Use E=1.12E' – 0.1 GeV for jet finding from an event list of tower energies that use the photon calibration (E')

Jet Reconstruction – Anti-k_T Jet Finder

Trigger on HCal masked ADC Sum in L/R Modules
Display anti-kT jet clusters satisfying acceptance cuts



- Anti-k_T Jet Finder Procedure :
  - Iteratively merge pairs of towers until towers cease to satisfy distance criteria
    - No Seed
    - Towers can be outside trigger region
  - Distance Criteria (clusters j,k) :
    - $d_{jk} = \min(k^{-2}_{Tj},k^{-2}_{Tk})(R^2_{jk}/R^2)$
    - $R^2_{jk} = (\eta_j - \eta_k)^2 + (\Phi_j - \Phi_k)^2$
    - If $d_{jk} < k^{-2}_{Tj}$ then merge clusters j,k
  - Use cone with $R_{jet} = 0.7$ in η-Φ space but cluster towers can fall outside of cone
  - Impose acceptance cuts to accept/reject jet:

    $|\eta_J - 3.25| < 0.25$

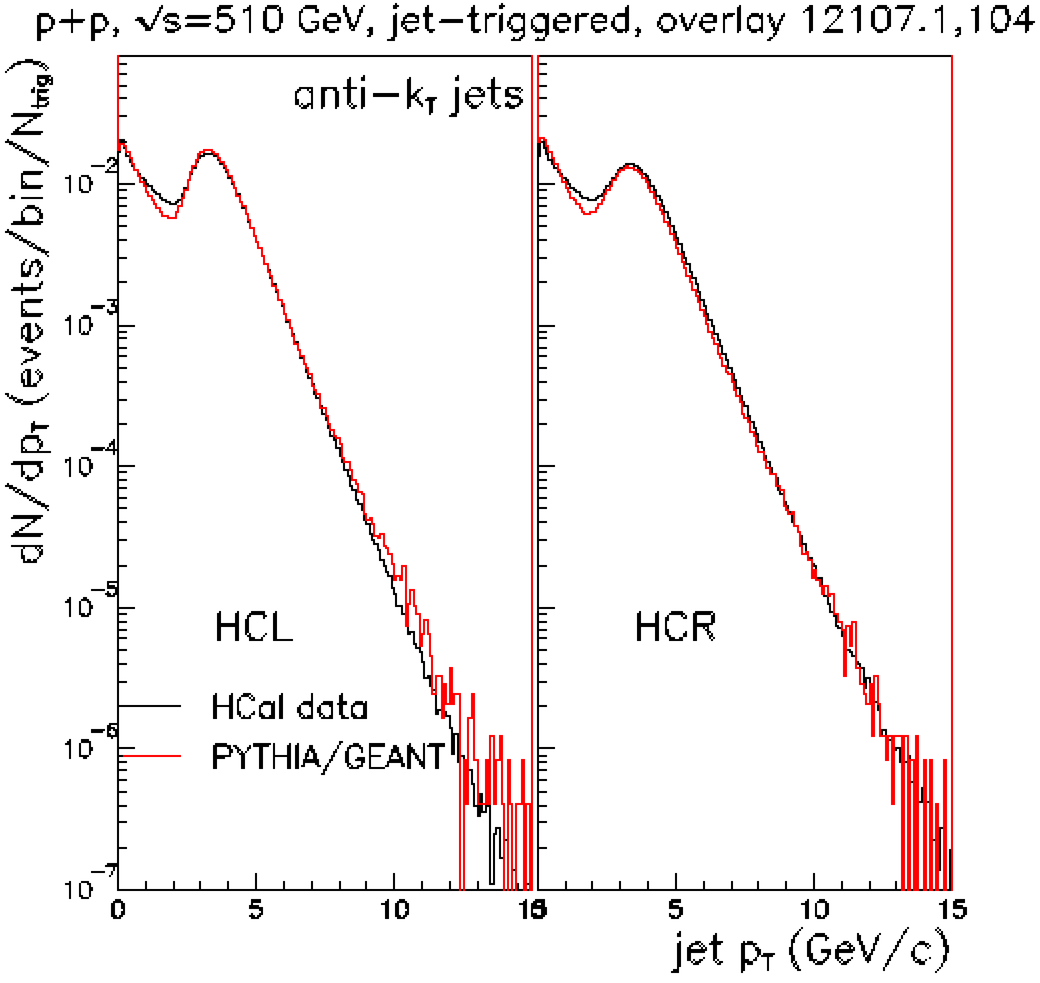
    $|\Phi_J - \Phi^{Off}| < 0.50$

    where $\Phi^{Off} = 0$ for HCL

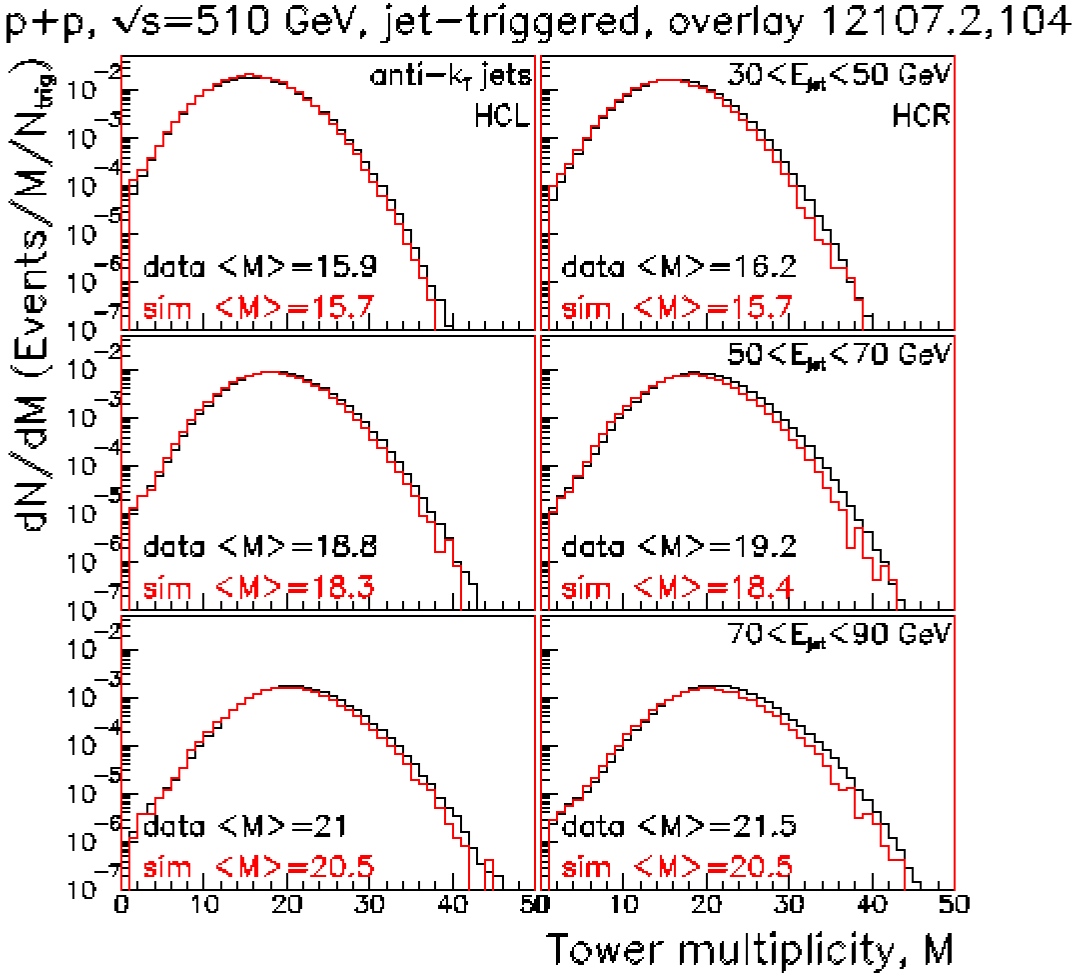
    $\Phi^{Off} = \pi$ for HCR
  - Energy Cut : $E_{jet} > 30$ GeV
  - Algorithm : arXiv : 0802.1189
    arxiv : 1209.1785

Events look "jetty" / Results with anti-kT algorithm similar to midpoint cone algorithm

Comparison of Data to PYTHIA 6.222/GEANT Simulation



Uncorrected p_T distribution of anti-kT clusters



Uncorrected multiplicity of towers in anti-kT cluster

Good description of data by simulation → use simulation for efficiency correction

What is a forward jet?

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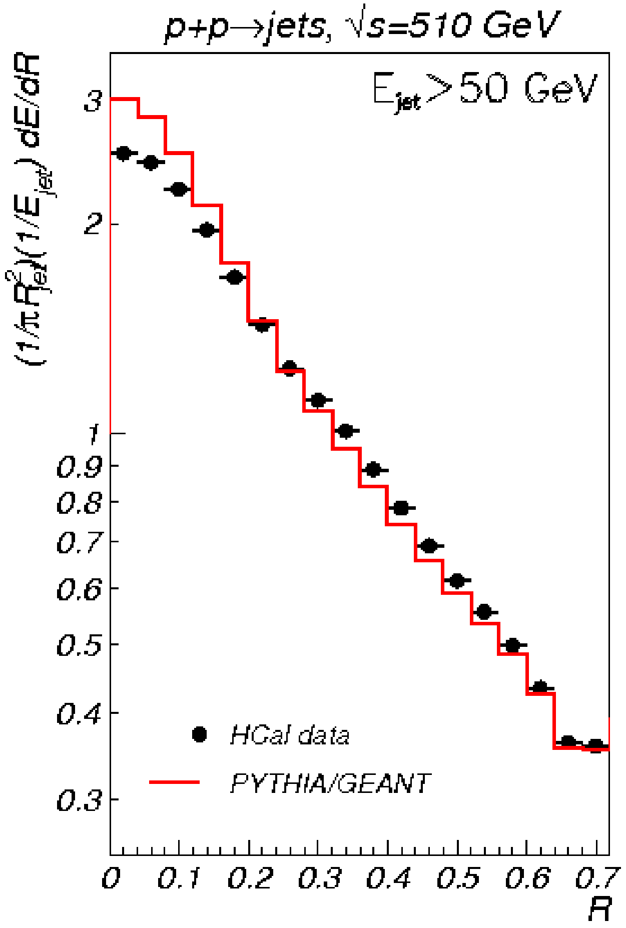
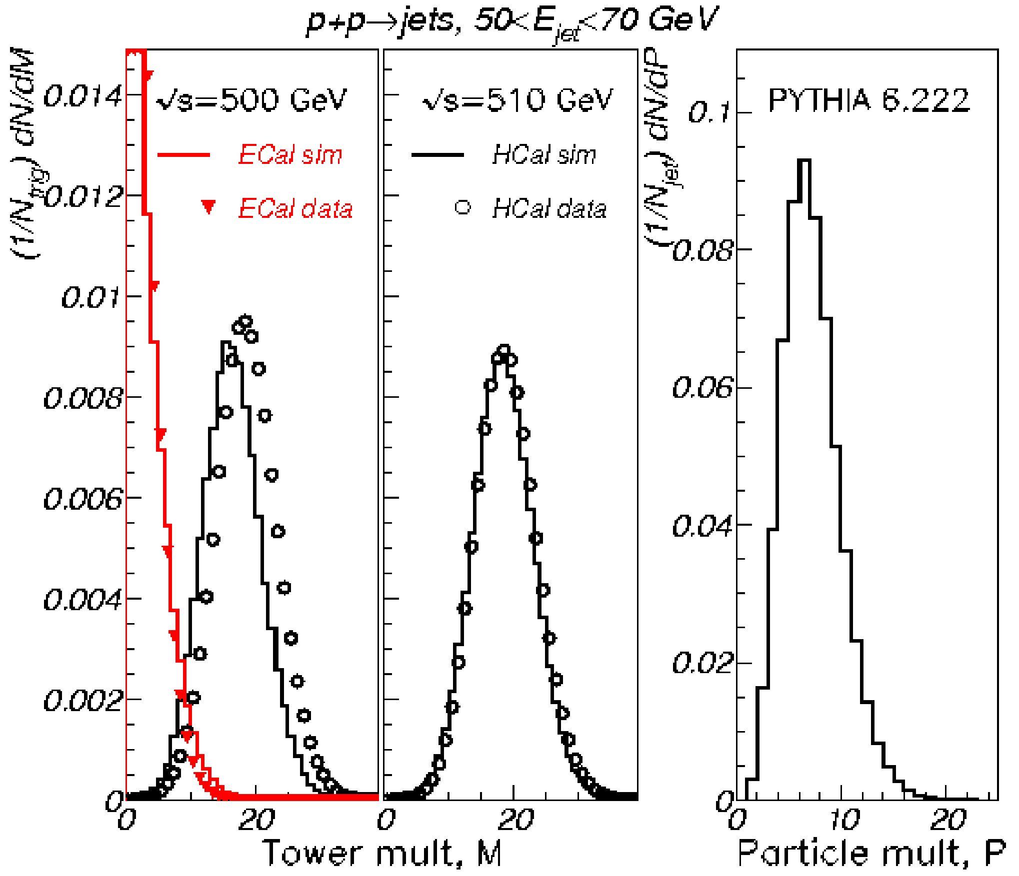
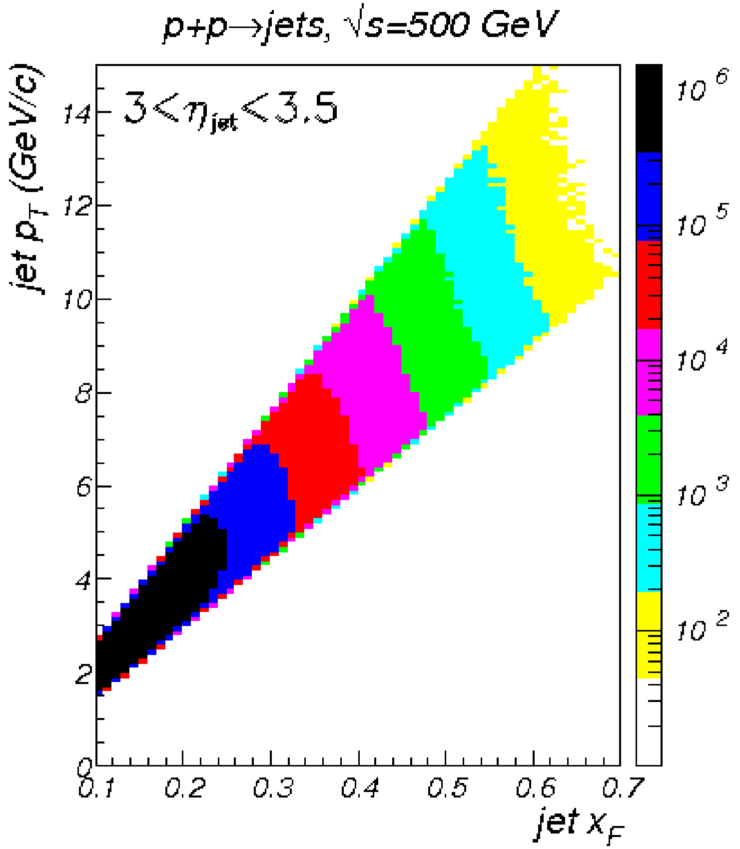






Event averaged jet shape: how the energy is distributed a distance R in η,φ from the thrust axis

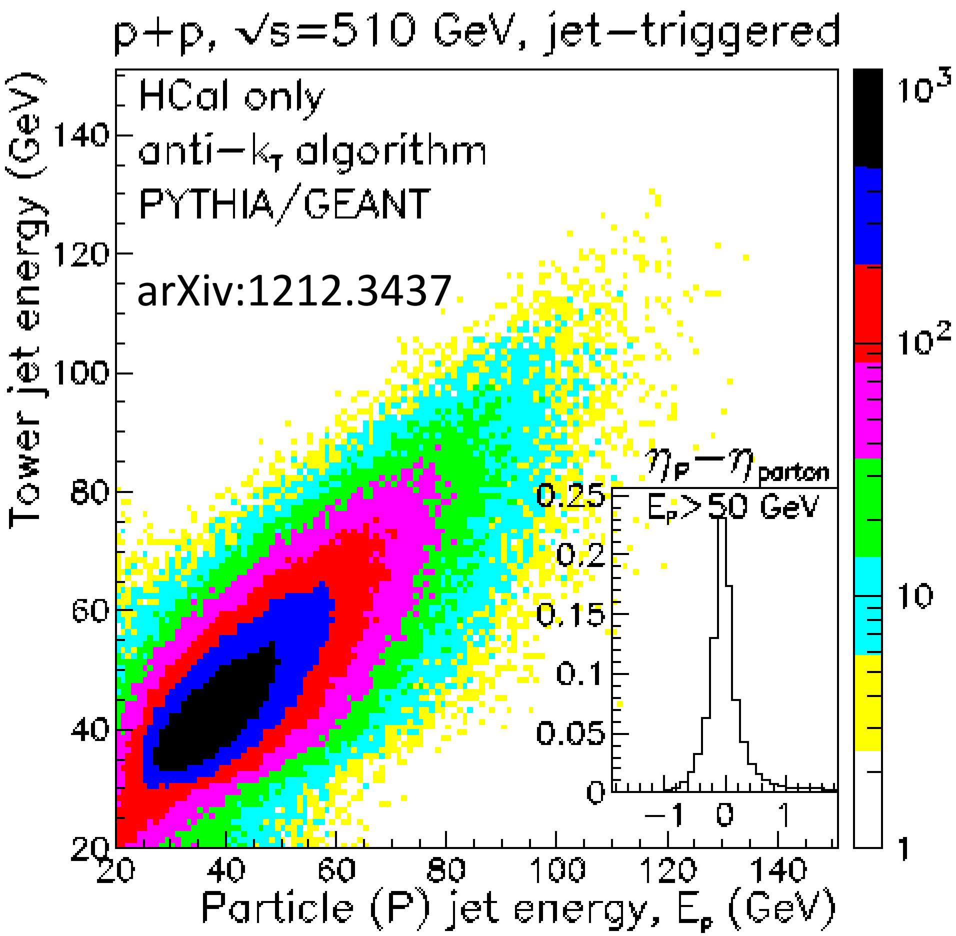
⇒ the anti-kT clusters have shapes similar to midrapidity jets

(left) tower multiplicities, as used for A_N;
(middle) tower multiplicities, as used for σ;
(right) incident particle multiplicity from simulation

⇒ multiplicity similar to jets of comparable scale

Acceptance of contained jets from particles with $2.4<\eta<4.2$ correlates x_F and p_T for the jet cluster

Jet Energy Scale - I



- Simulations confirm energy scale of jets, by comparison of "tower" jets [with full detector response] to "particle" jets [excluding detector response].
- Reconstructed jets are directionally matched to hard-scattered partons as generated by PYTHIA

Correlation between tower jet [from PYTHIA/GEANT] to particle jet [from PYTHIA]. The inset shows the η component of the directional match (Δη) between particle jets and a hard-scattered parton, whose direction is defined by ηparton,φparton. There is a 82% match requiring |Δη|,|Δφ|<0.8

Jet Energy Scale - II

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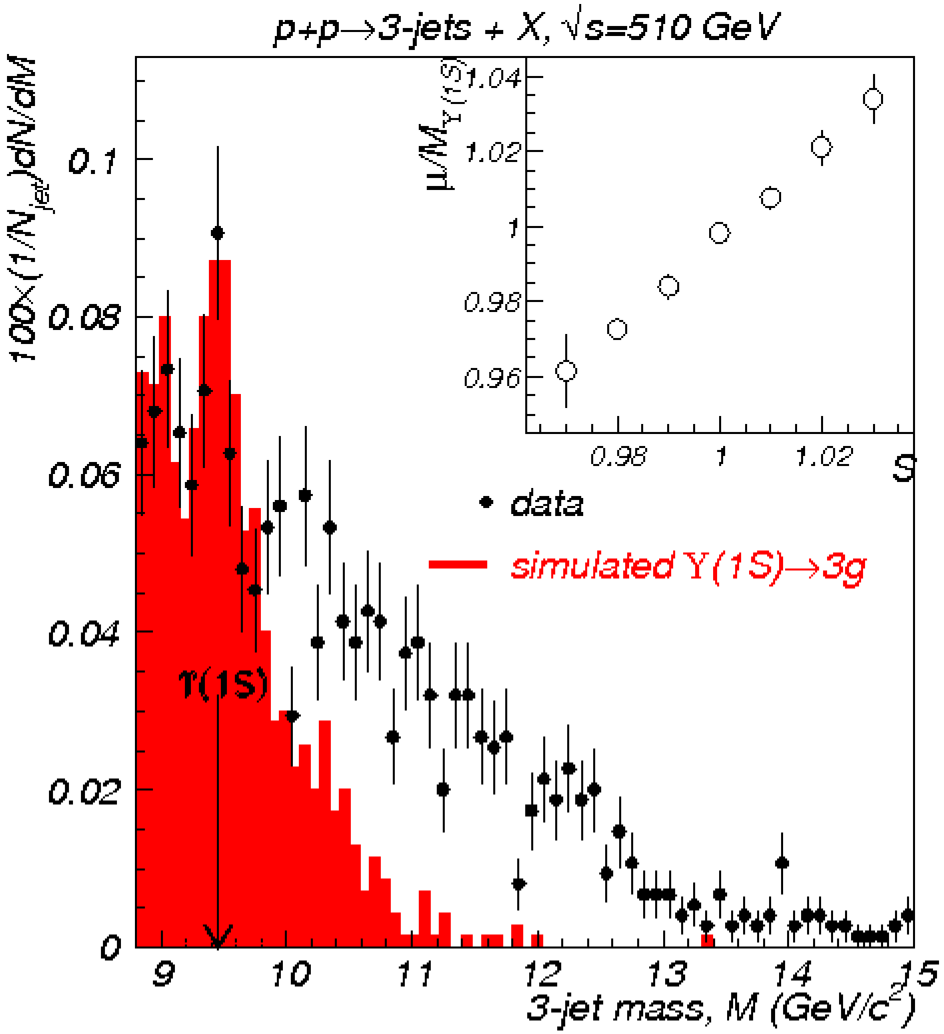

- Test jet energy scale by reconstruction of invariant mass for multi-jet events
- Observe 3.5σ statistical significance peak, attributed to $\Upsilon(1S)\rightarrow 3g$. The red overlay is a simulation of the signal from the PYONIA generator of $\Upsilon(1S)\rightarrow 3g$, run through GEANT, and then reconstructed as done for the data
- For the inset, S rescales the energy calibrations, so tests the jet-energy scale.
- Peaks are also observed in 2-jet mass attributed to $\chi_{2b}\rightarrow 2$ gluons. Peaks in N-jet events require large multiplicity [ΣQ from beam-beam counter] ~7 units of rapidity away from dijet [aXiv:1308.4705]

Forward Jet Cross Sections

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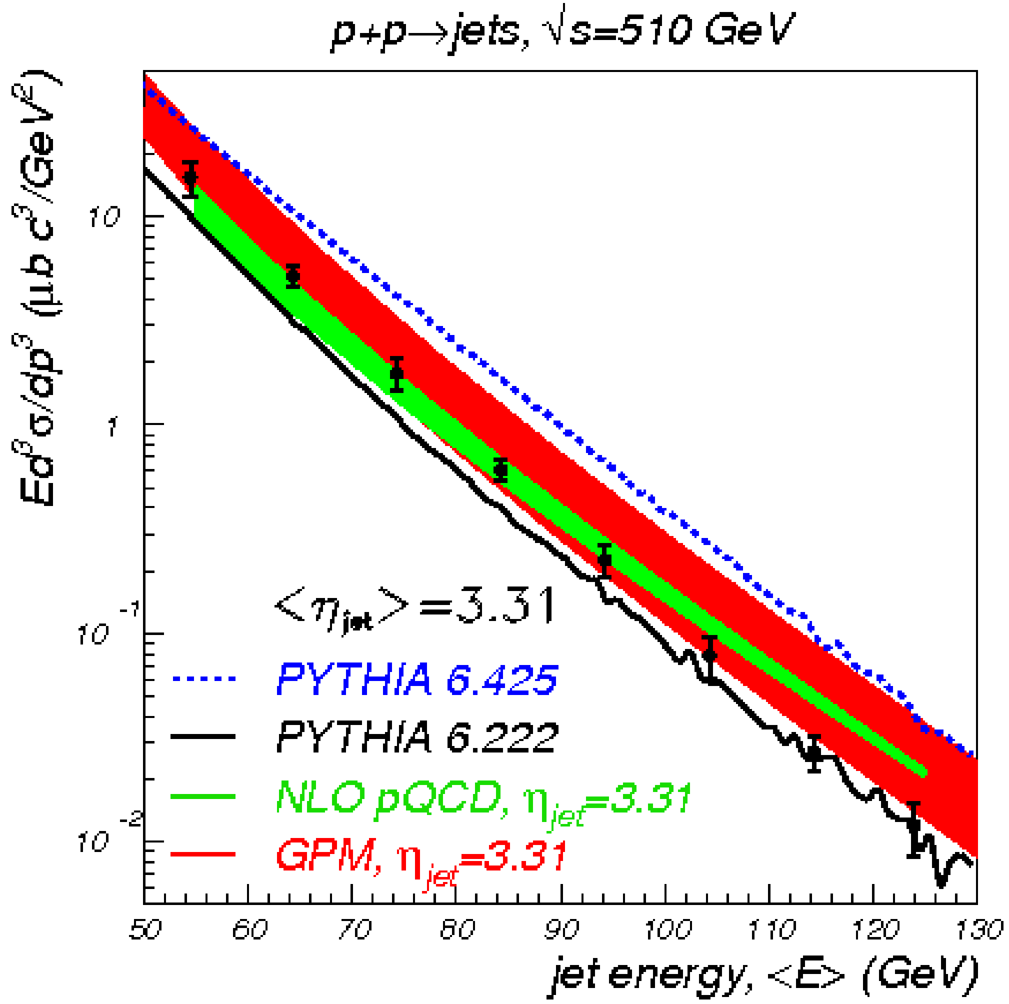


- Uncertainties include both statistical and systematic estimates [as described in backup]

- Strong dependence on both x_F and p_T requires data/theory comparisons at $<\eta_{jet}>$

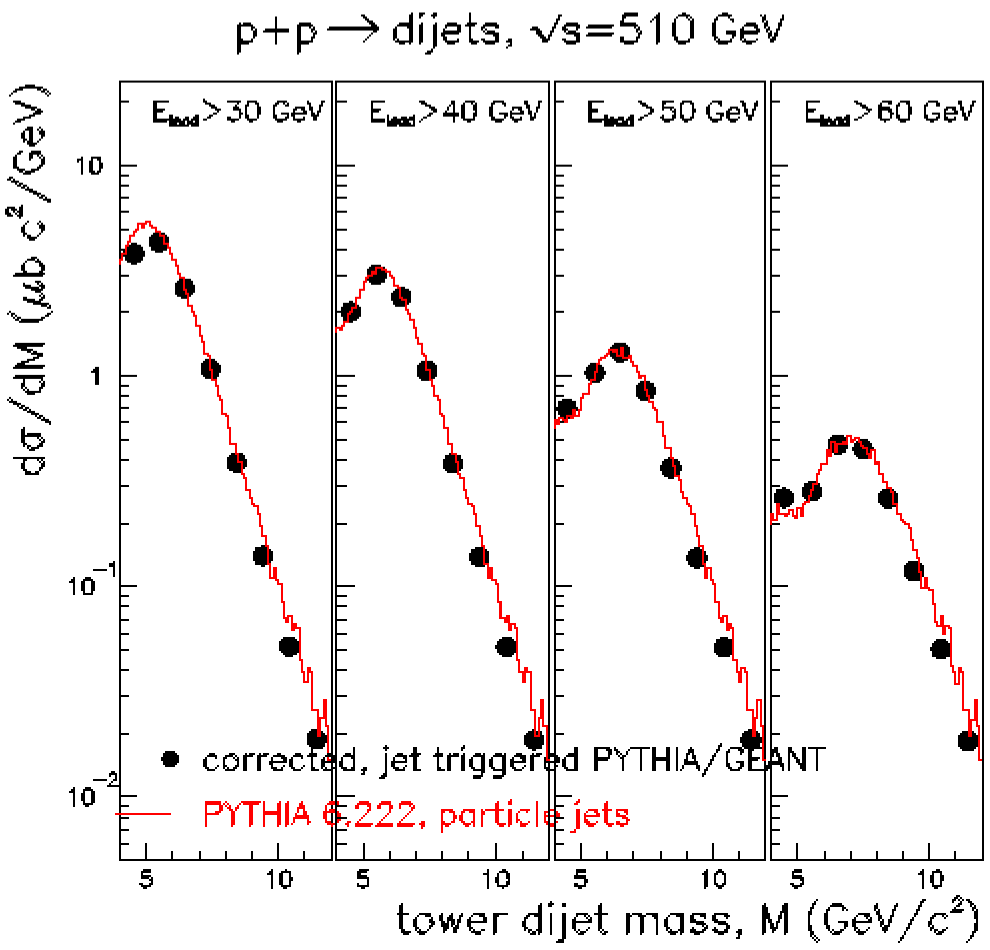
- NLO pQCD [PRD 86 (2012) 094009] calculation provides a good description of the data using CTEQ6.6M PDF. Note the small scale dependence [band represents range of scale from $\mu=2p_T$ to $\mu=p_T/2$]

- Leading-order pQCD model calculation assuming factorization in the use of k_T dependent distribution functions [generalized parton model (GPM), PRD 88 (2013) 054023] also describes the data. The larger scale dependence is likely a consequence of a leading-order calculation

- Particle jet reconstructions [no detector effects beyond acceptance] with the anti-kT algorithm with $R_{jet}=0.7$ are used to compare default PYTHIA 6.222 [prior to tunings for the LHC] and PYTHIA 6.425 ["Field tune A"] to data. PYTHIA 6.222 was previously found to describe forward π^0 production at $\sqrt{s}=200$ GeV [arXiv:hep-ex/040312].

Test of Dijet Corrections

Comparison of corrected PYTHIA/GEANT tower dijets to PTYHIA particle dijets



- It is found that the dijet $\varepsilon_{trig}(V)$ [for $V=M,k_T,p_z$] is the only correction required; i.e., $\varepsilon_{det}(V)=1$
- The dijet correction procedure when applied to PYTHIA/GEANT tower dijets reproduces the input PYTHIA particle dijets (animate for $V=k_T$ and p_z distributions)
- Require $M>4$ GeV/c^2 when reporting $d\sigma/dk_T$ and $d\sigma/dp_z$.

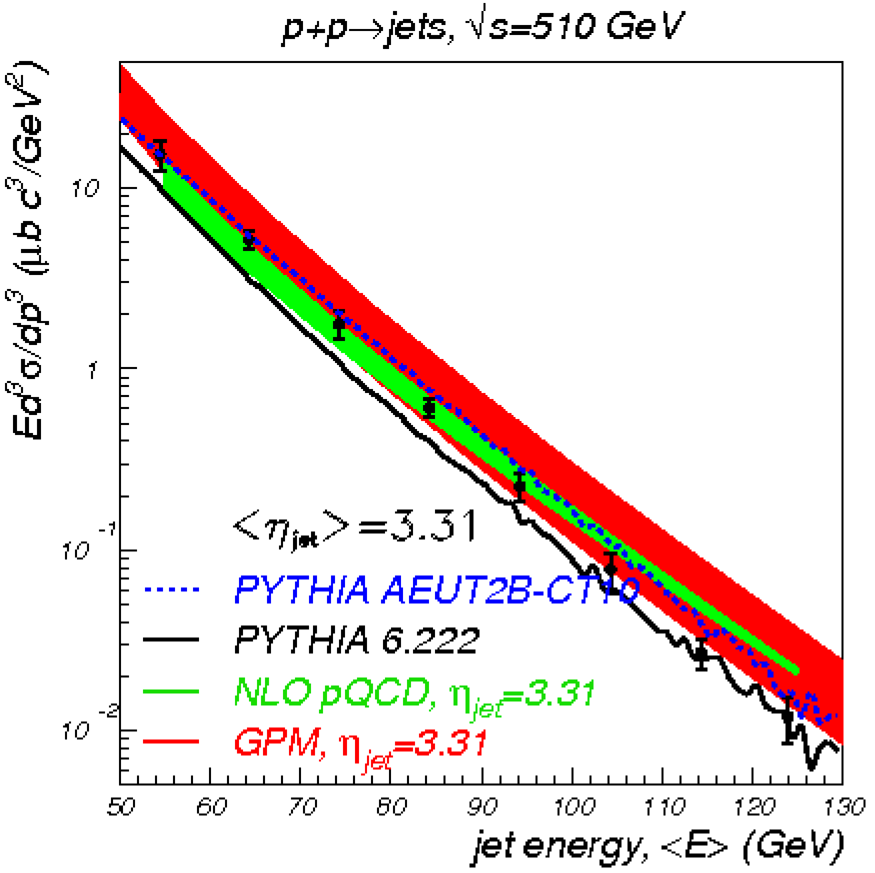
PYTHIA Tunings

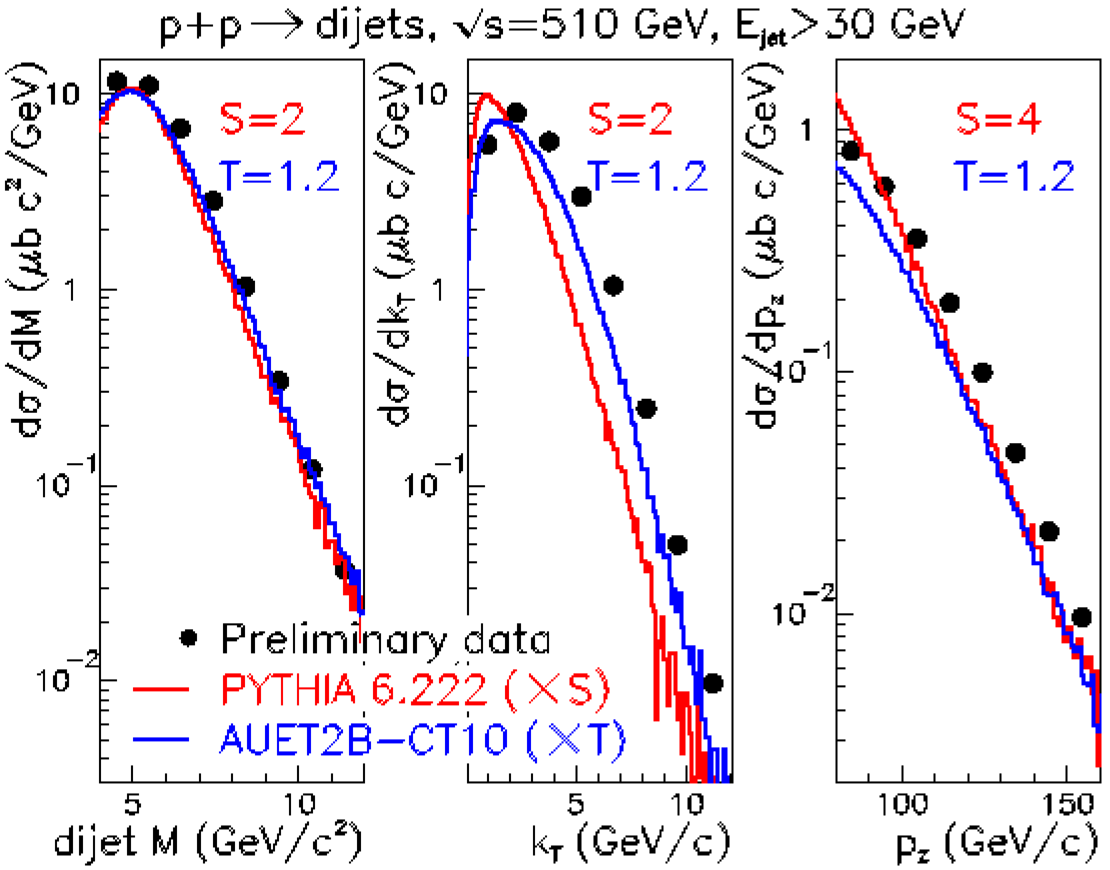
- The LHC high-energy program has prompted many retunings of PYTHIA, so that backgrounds in e.g. dijet mass are well modeled to allow new particle searches. See P.Z. Skands, PRD 82 (2010) 074018 [arXiv:1005.3457]

- PYTHIA tunings most commonly adjust initial-state and final-state showering parameters; multi-parton interaction model parameters; etc. As will be shown, inclusive forward jets and forward dijets from RHIC are sensitive to these tunings [as should be expected, since the rapidities involved for forward dijets at RHIC rival those from midrapidity at the LHC]

- In general, any serious low-x physics study of forward particle production will need to deal with the physics of parton showers and multi-parton interactions. It is not good to attempt to "correct" measurements for these effects. Experimental results should report what's observed, rather than subtracting model-dependent quantities from what is measured [in my opinion…]

Data versus Atlas [AUET2B with CTEQ10] Tune





- This is AUET2B-CT6L as developed by Atlas [arXiv:1512.00197 / PLB 756 (2016) 10], replacing the PDF by CTEQ10 [which differs from CTEQ6 for low-x gluons]
- Reasonable description of inclusive jet data
- ~20% overprediction of dijet data

Extending Gluon Polarization Measurements to Low-x

- Installation of forward calorimetry that combines good electromagnetic and hadronic responses at STAR or PHENIX can allow measurement of A_{LL} for forward dijet production at $\sqrt{s}$=510 GeV.

- Careful evaluations of global analyses [arXiv:1407.4176] leads to expectations that A_{LL}~10^{-3} for forward dijets in p+p collisions at $\sqrt{s}$=510 GeV, which can be measured with both statistical and systematic significance in a future RHIC run.

- The basic requirements to extend gluon polarization measurements to low-x are a well-understood forward jet detector, high-luminosity operation of RHIC with longitudinally polarized colliding protons, and good solutions to environmental issues

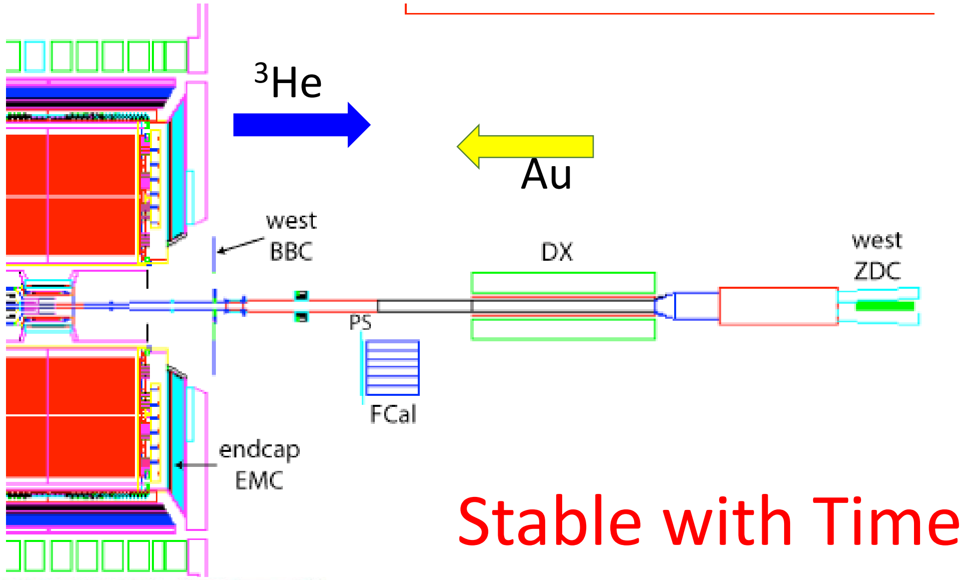
Issues for Installation of Forward Calorimeter at STAR

- 2-m hole in east and west poletips of STAR solenoid provides a window to forward physics
- The 0.5-T central field in the STAR solenoid produces large (~0.01T) longitudinal magnetic fields at the location of an FCal, typically parallel to desired locations of photosensors, thereby making it difficult to shield phototubes
- Radiation effects from high-luminosity RHIC operation can impact the calorimeter and/or the photosensors [e.g. silicon photomultipliers]

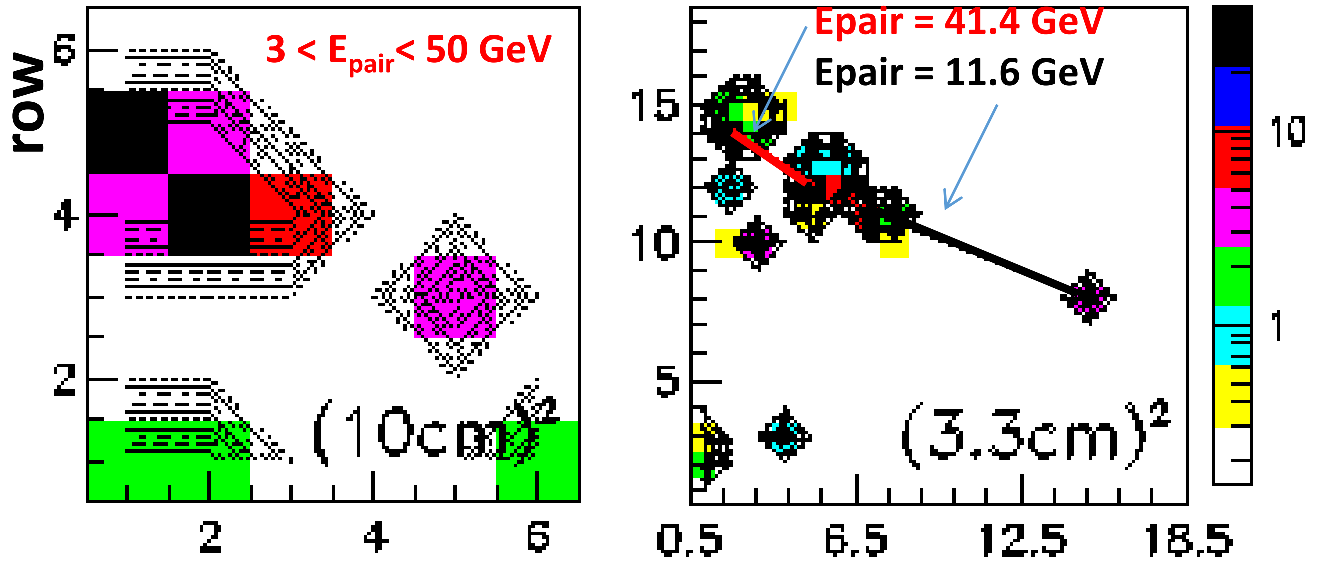
We have addressed these issues in tests at STAR in 2014 and 2016

The proposed calorimeter has been tested at FermiLab in 2015

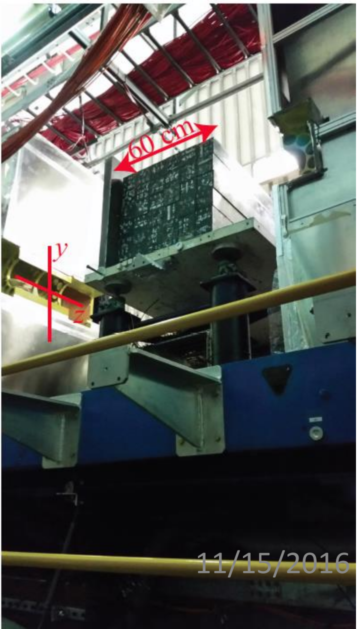
Run14 Prototype FCal

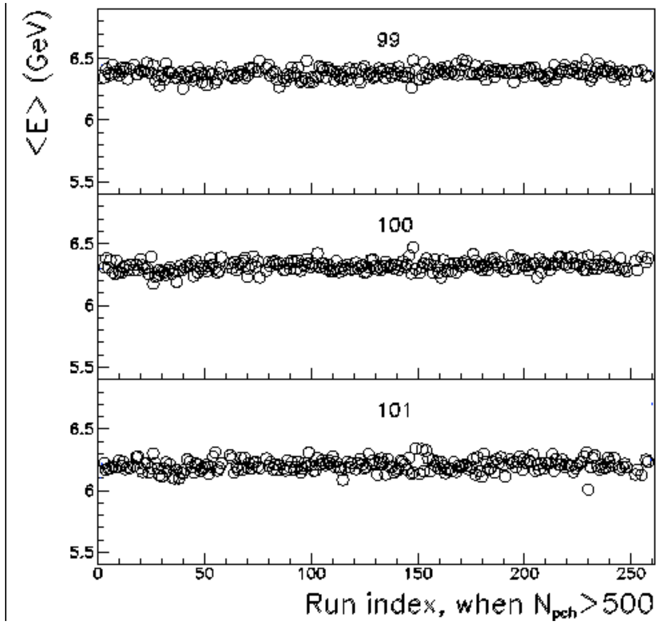


from $(10cm)^2$ cells to $(3.3cm)^2$ pixels



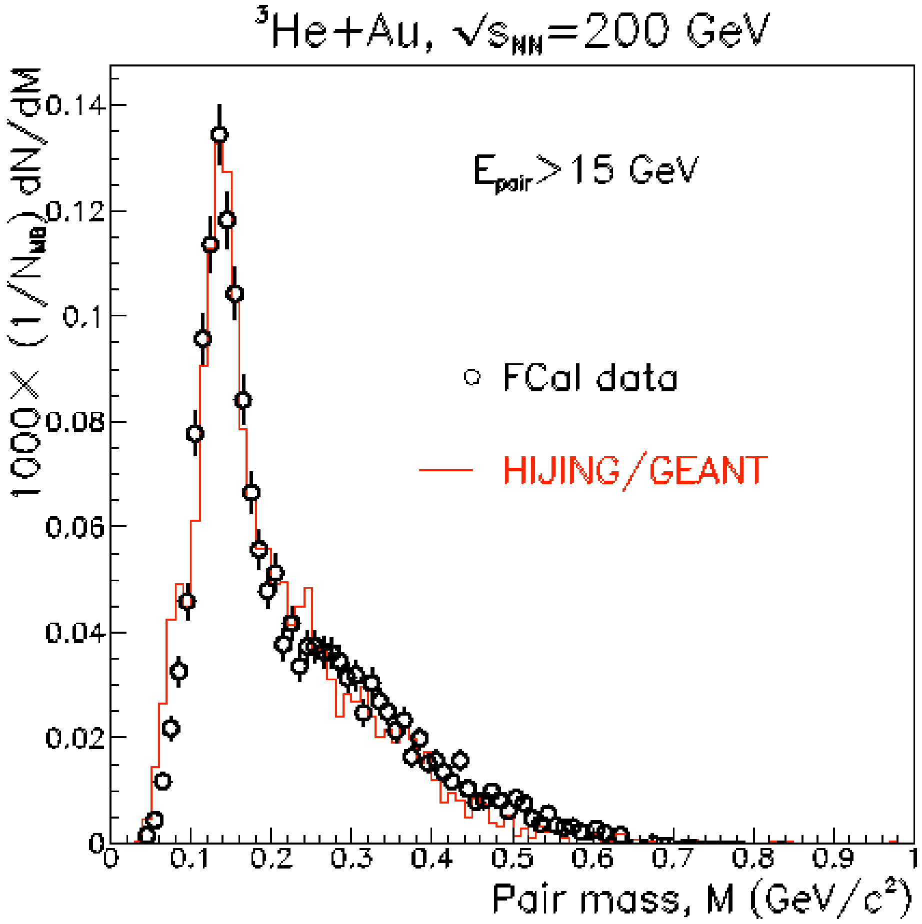
Stable with Time

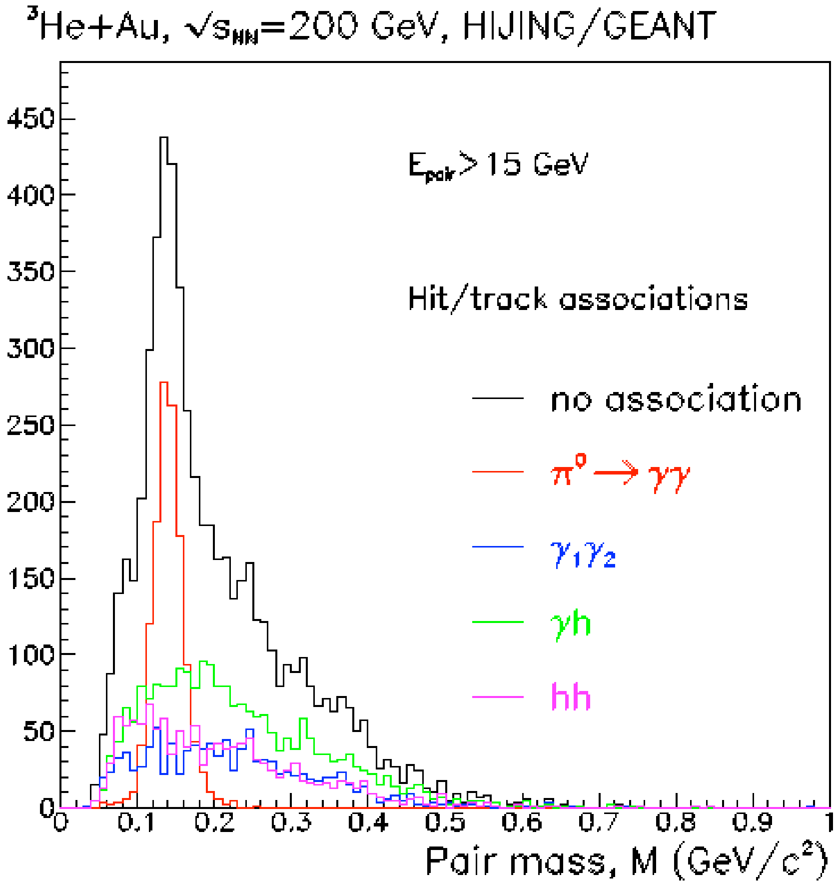




- Pixelizing 36 E864 cells into 324 $(3.3cm)^2$ pixels allows reconstruction of neutral pions to higher energy up to ~50 GeV
- FCAL was stable through ^{3}He+Au collision
- Radiation Hardness - no energy re-calibration required over duration of ^{3}He+Au running

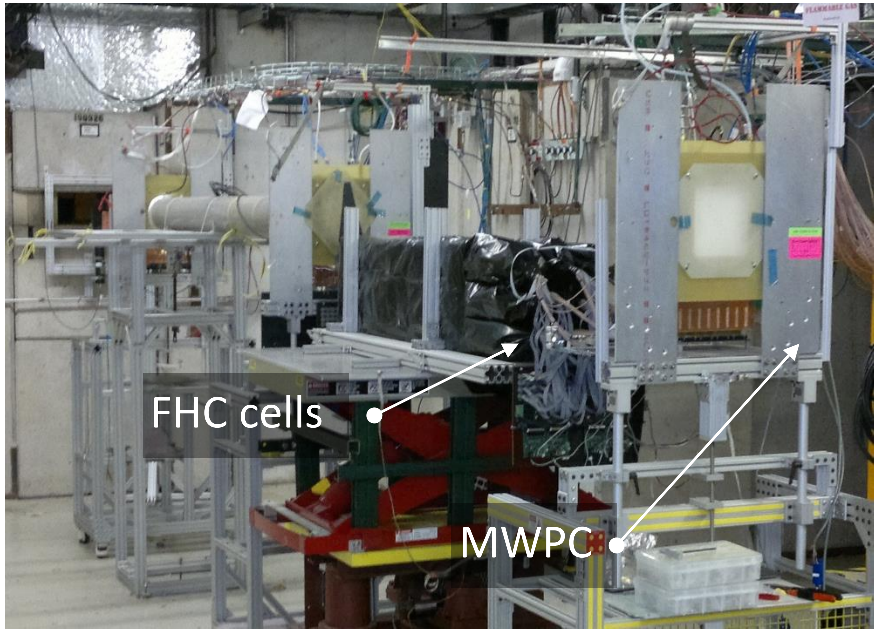
Data vs. Simulation

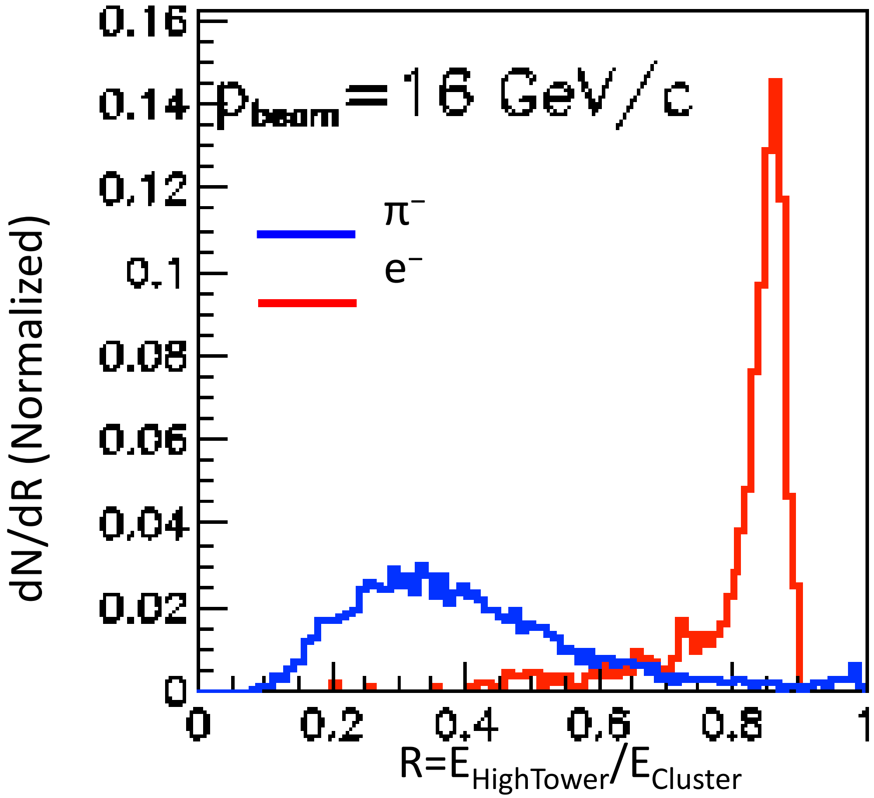


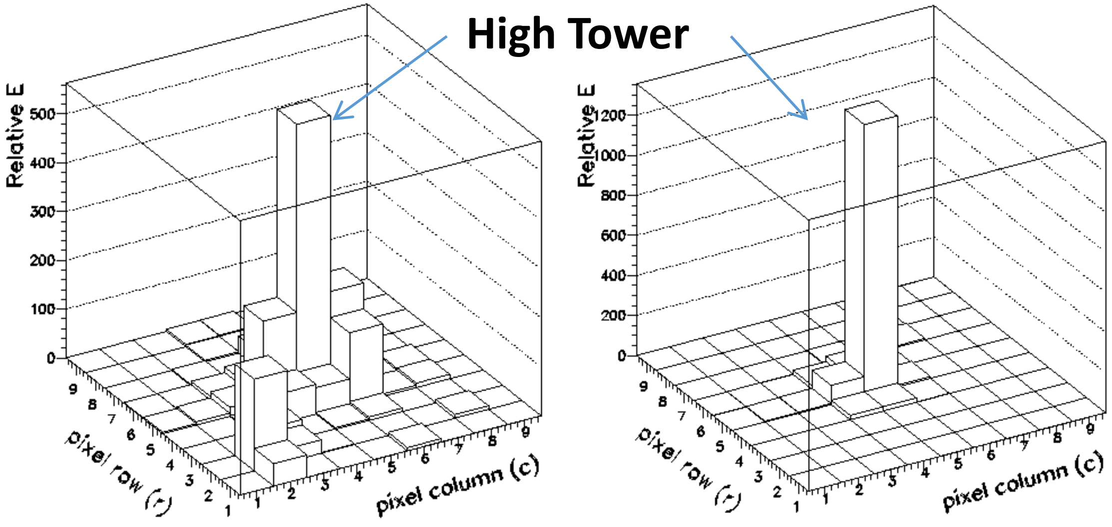


- Hits/Clusters were identified using associated particles in simulation
- Dominant background is when one cluster is a photon and the other is a hadron
  - Can be effectively reduced by good pre-shower detector and additional e/h discrimination from FCal

FTBF Test Beam / T1064







π^- 16 GeV/c

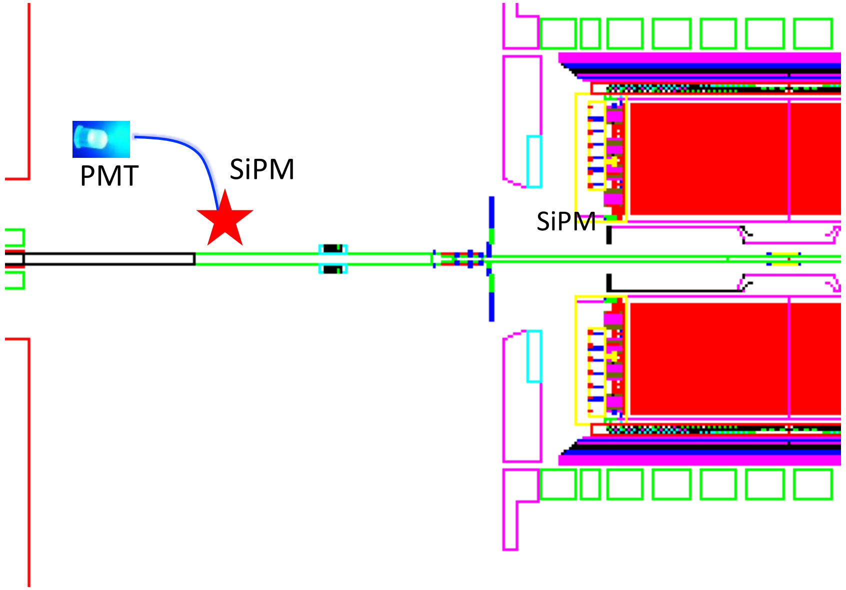
e^- 16 GeV/c

- Shows clean separation between e^- & π^- shower shapes
- Hadronic shower shapes can be distinguished from EM showers with greater than 90% confidence

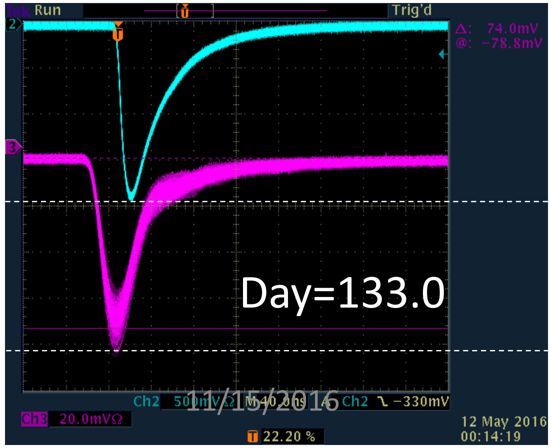
FTBF: Fermilab Test Beam Facility
http://ppd.fnal.gov/ftbf/

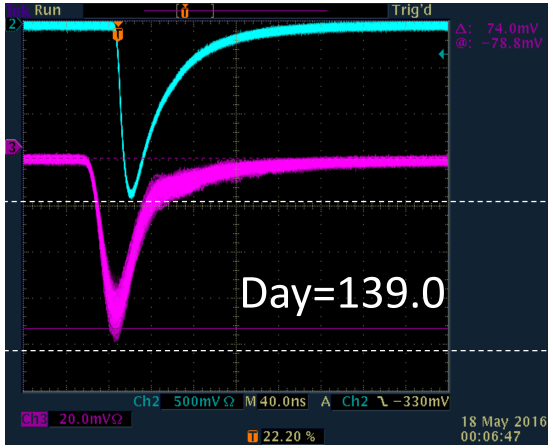
SiPM Irradiation Tests - 2016

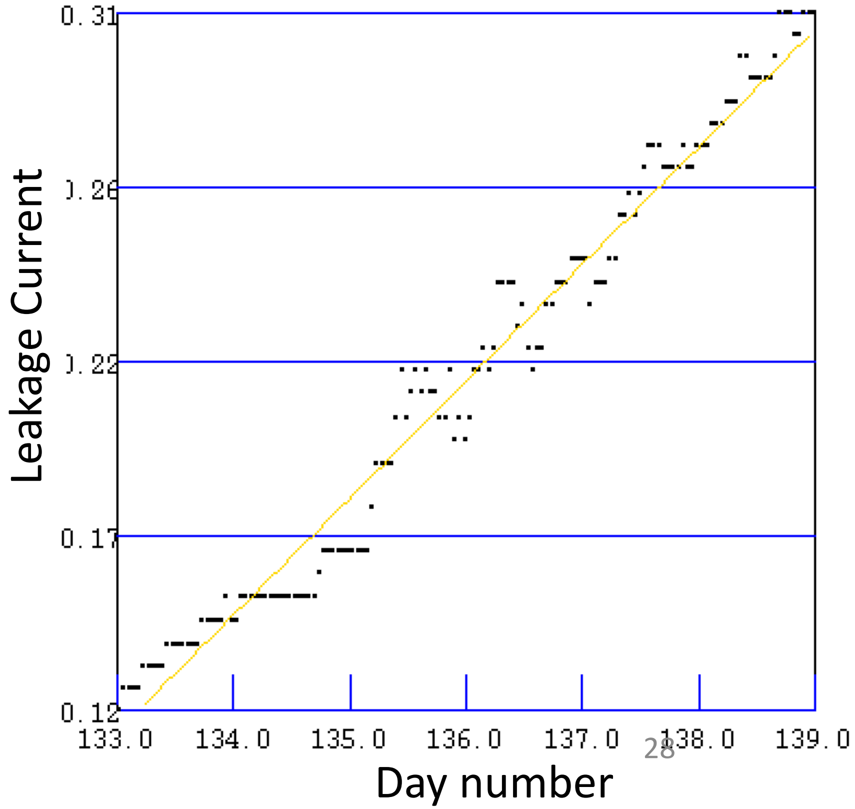
- No/minimum magnetic field effects and low cost compared to PMTs
  - But, can be subject to radiation effects
- SiPMs were illuminated by a pulsed (100Hz) blue LED light source
- Exposed to d+Au background radiation
- SiPM leakage current increases with time
- Loses gain with increasing leakage current
  - Impact FCAL stability over time



PMT: Blue, SiPM: Magenta





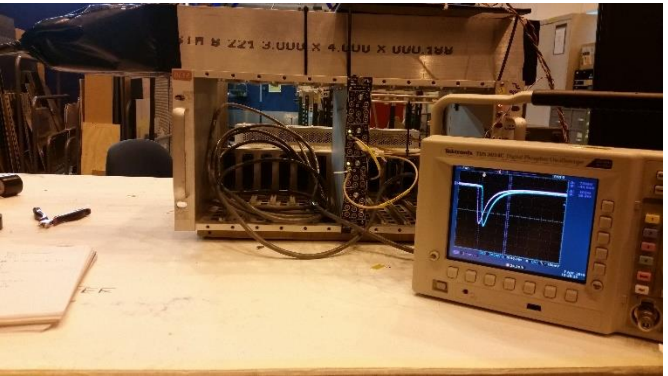


Magnetic Field Test

- Dominant fringe field from the STAR solenoid and DX magnet is B_z
- Apparatus with PMT and flashing LED is placed at the east side of STAR
  - 4.1^0 angle with respect to the z-axis
  - Monitored when STAR solenoid + RHIC DX magnet is excited, using network programmable oscilloscope

XP2262 (2” diameter)
- **Enough space 30-mil mu-metal**
- **Negligible gain shift**

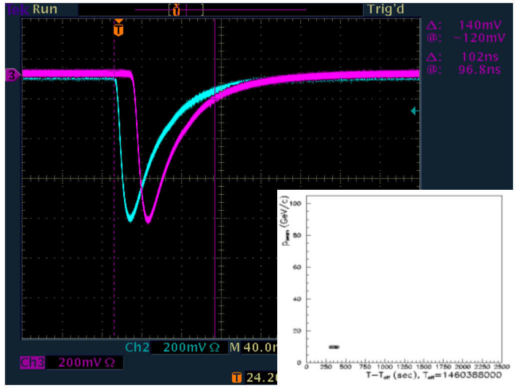
XP2972 (1.125” diameter)
- **15% downward gain shift for 10-mil mu-metal**
- **Few percent gain shift for 20-mil mu-metal**



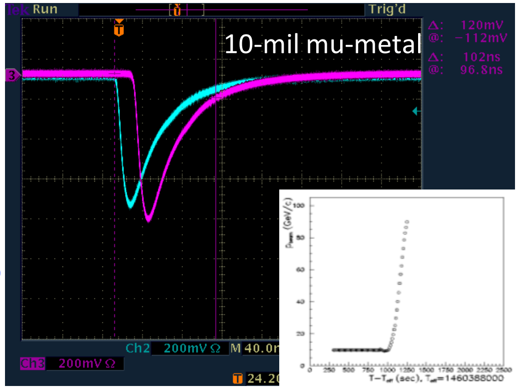
Mu-metal: Ni-Fe magnetic alloy, shield static or low frequency magnetic field

STAR magnet – Zero Field

DX magnets at injection



DX magnets at full current



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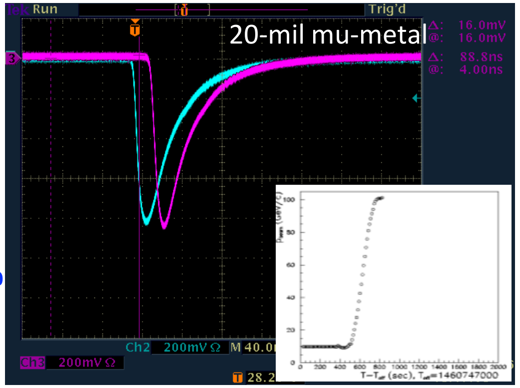

Blue: XP2972

Magenta: XP2262

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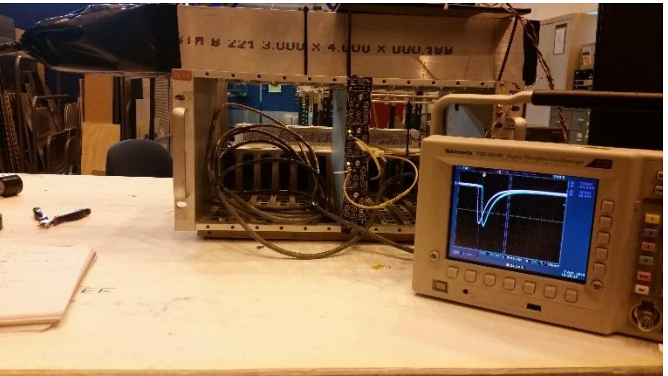

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DX Magnet – Zero Field

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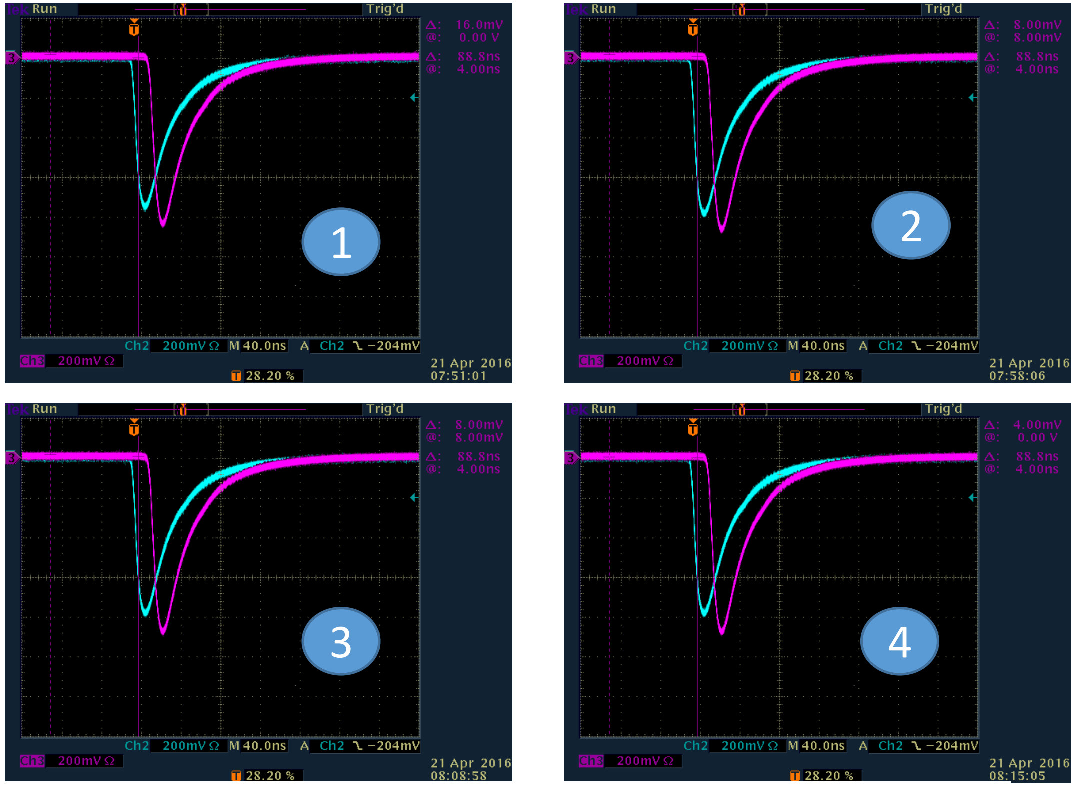
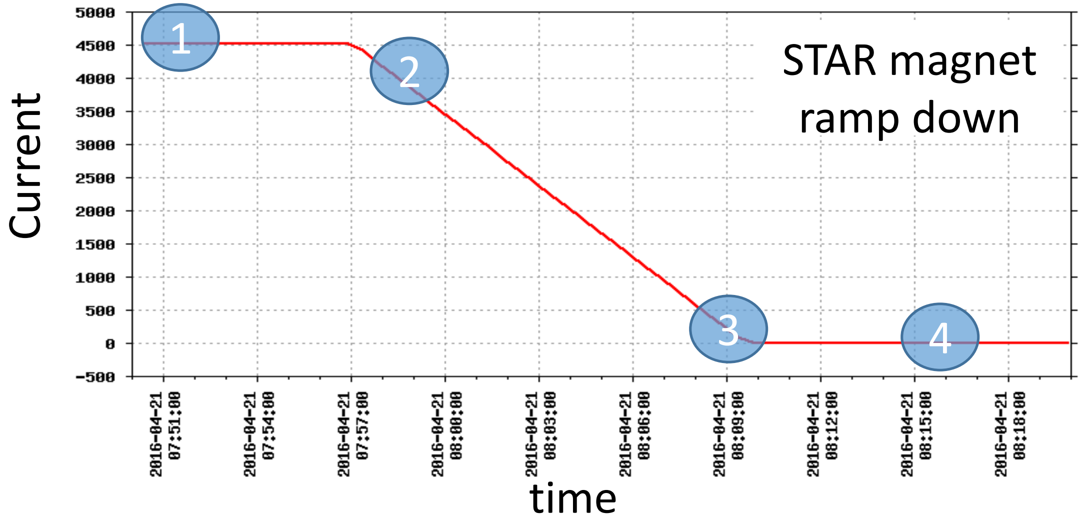
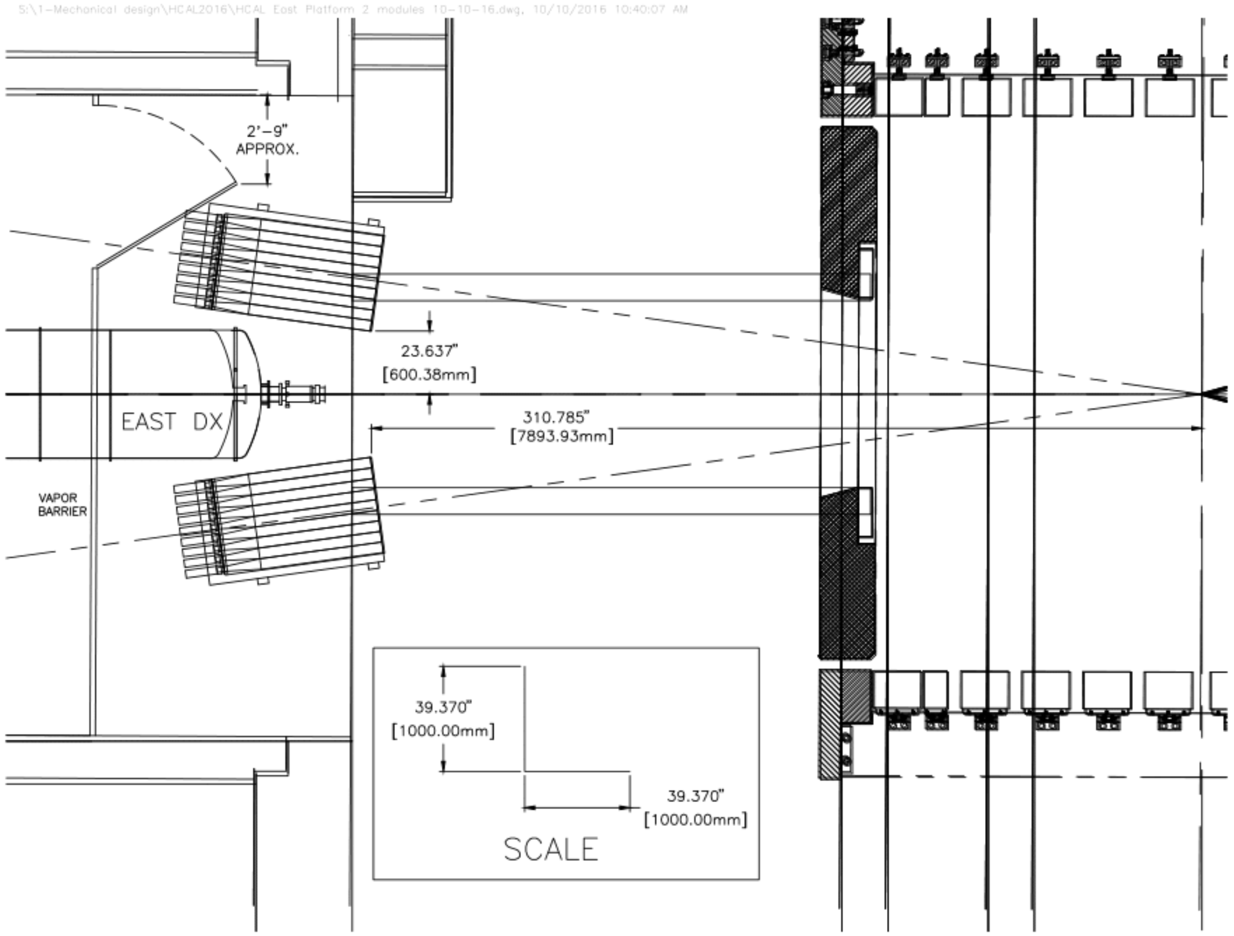
Magenta: XP2262





Proposed Location for FCal

$2.7 < -\eta < 3.7$



Drawing courtesy of John Scheblein

- Edge of east tunnel opening to wide angle hall
- No modifications to east support platform required
- FCal personnel will stack calorimeter in place. Only minimal technical help is required
- Existing rack on floor of wide angle hall to the south of the beam will be used $\Rightarrow$ no electrician work required
- Existing cabling from IP2 effort will get used $\Rightarrow$ minimal cost
- It is required to move the vapor barrier further to the east to make room for FCal

Who is involved?

- Lehigh University – Rosi Reed, Prashanth Shanmuganathan, Daniel Brown, Justin Ewigleben
- Temple University – Bernd Surrow, Matt Posik
- Berkeley – Hank Crawford, Jack Engelage, Chris Perkins, Eleanor Judd
- IHEP, Protvino – Larisa Nogach
- Brookhaven – Les Bland

Others welcomed! This is a great hands-on project for students.

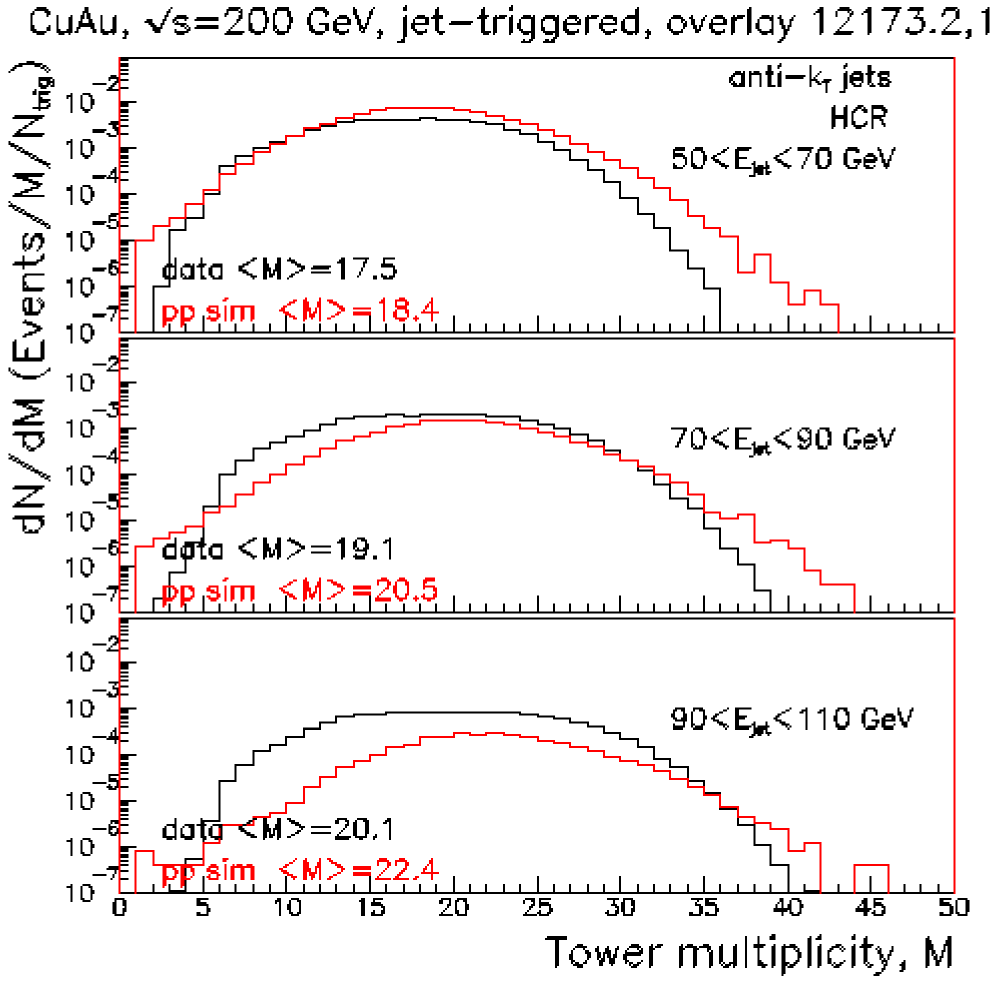
Temple/Lehigh FCal meeting at Temple University on 11 August 2016

Broad Impact of Improved Forward Instrumentation

$\Rightarrow$ applications in (light) heavy-ion collisions

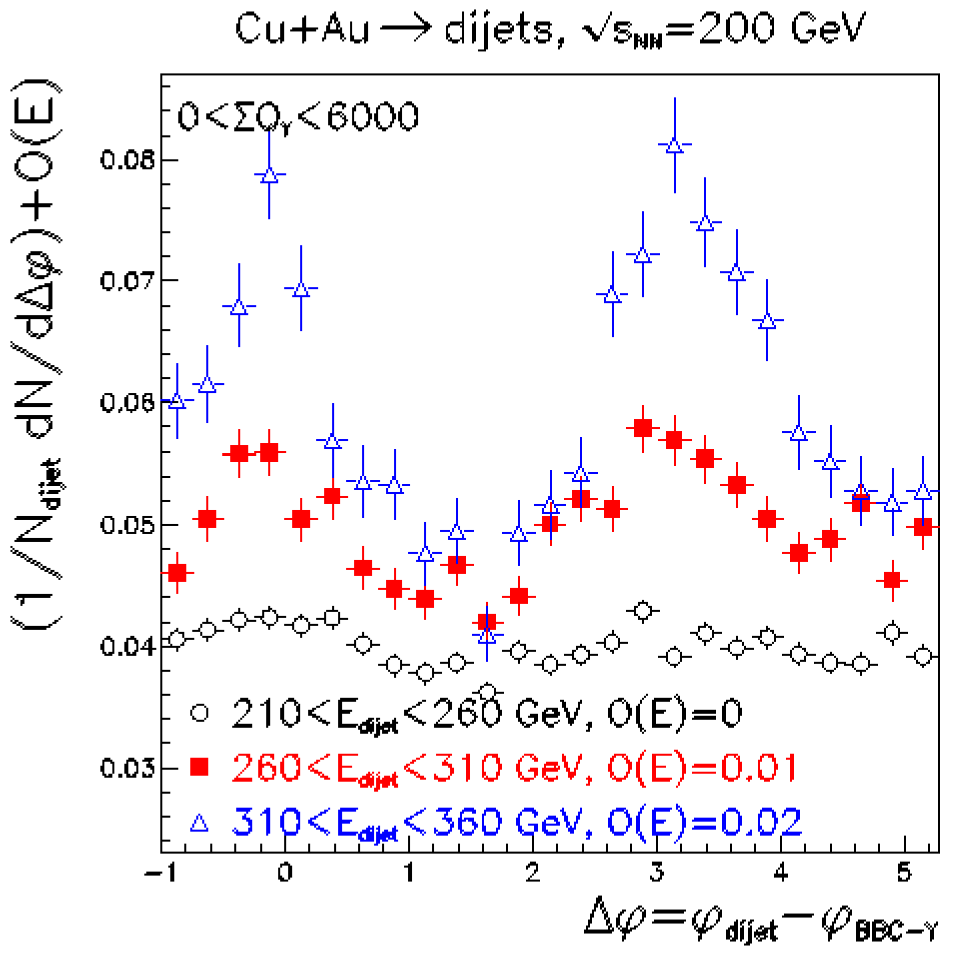
Forward Jets and Dijets in Cu+Au at $\sqrt{s_{NN}}$=200 GeV

$3.0<\eta_{jet}<3.5$



- The jet finder is applied to a small sample of Cu+Au collisions at $\sqrt{s_{NN}}$=200 GeV, selecting peripheral collisions. Jet tower multiplicities are similar to p+p jets of the same energy
- Jets and dijets are in the Cu beam direction
- Inclusive jets in Cu+Au collisions extend beyond 100 GeV, which exceeds Feynman-x scaling limits for N+N collisions $\Rightarrow$ analogous to radial flow? and/or particle production from collective nuclear effects?

Forward Jets and Dijets in Cu+Au at $\sqrt{s_{NN}}$=200 GeV



O(E) offsets the azimuthal correlation for each E_{dijet} bin

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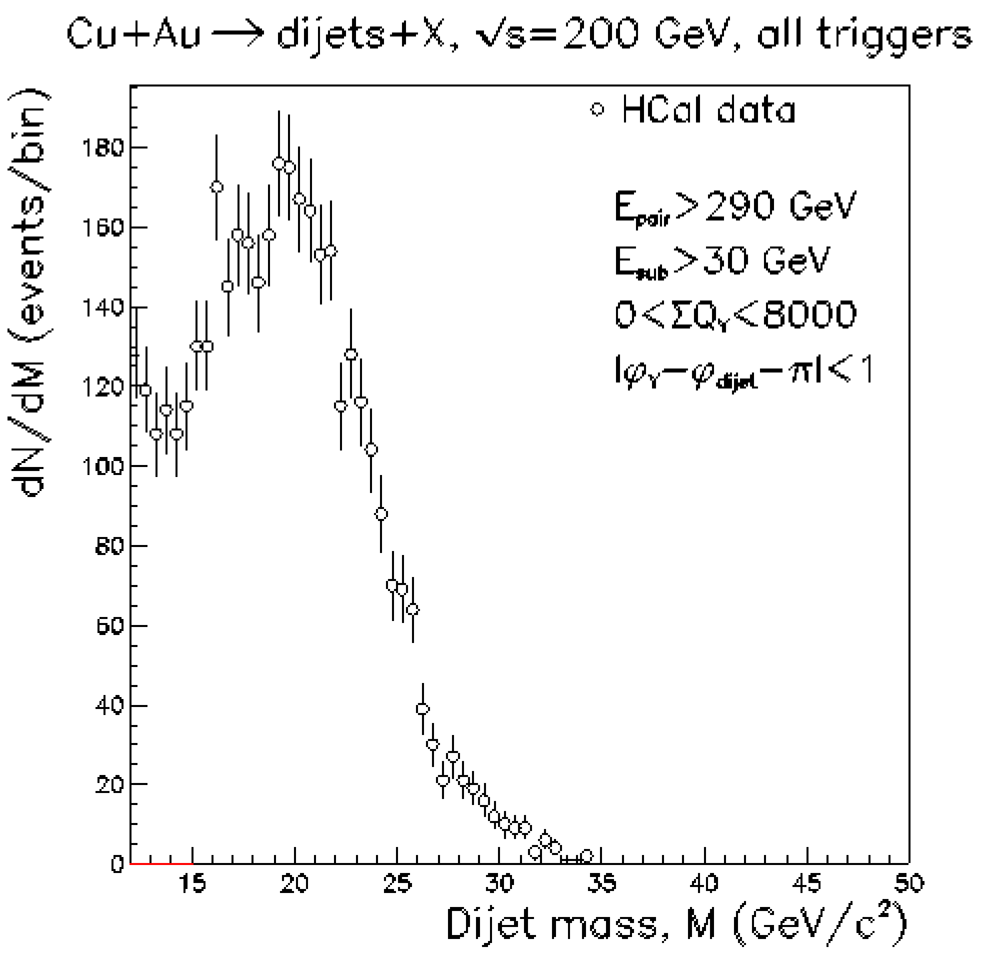
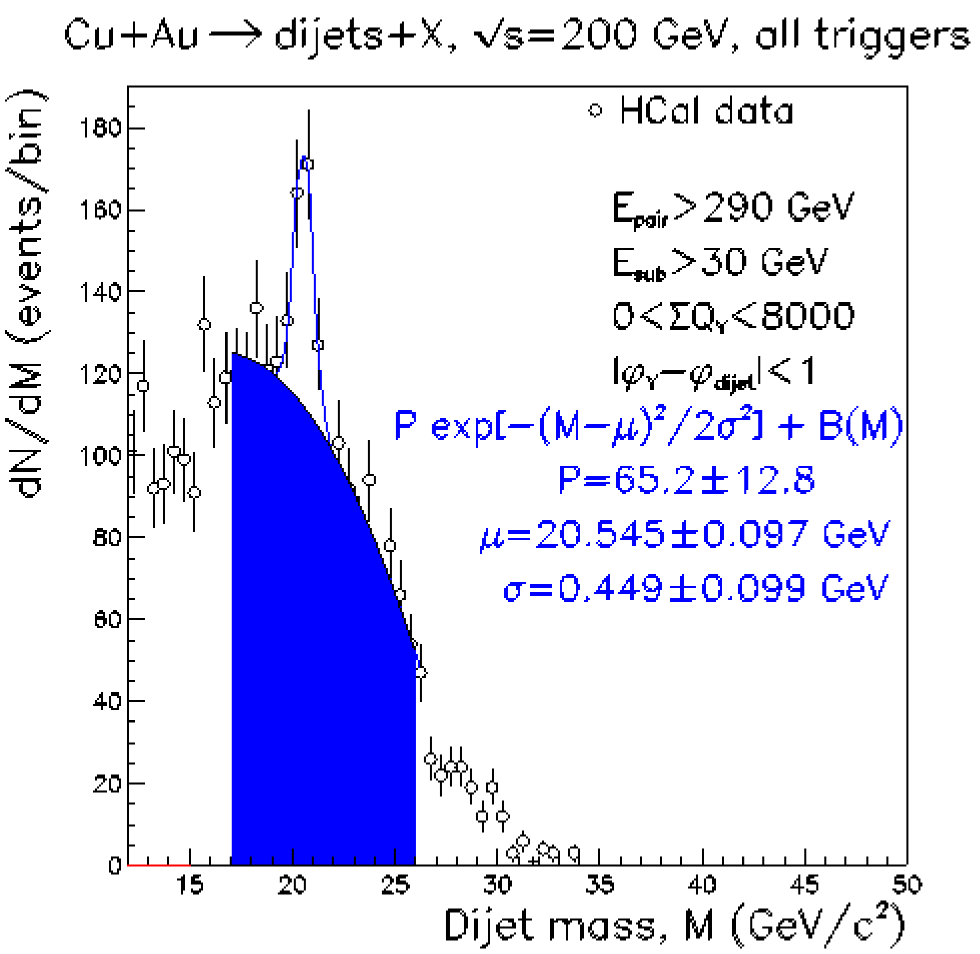
- Jets and dijets are in Cu beam direction
- Inclusive jets in Cu+Au collisions extend beyond 100 GeV, which exceeds Feynman-x scaling limits for N+N collision
- Forward dijets in Cu+Au collisions have strong azimuthal correlations with particles 7 units of rapidity away [analogous to CMS results (JHEP 09 (2010) 91)], as measured via total charge in beam-beam counter annulus facing Au beam
- With FCal at STAR the rapidity interval from $-1<\eta<+4$ can be examined for a near-side ridge
- Long-range rapidity correlations can be explored between a forward jet at η~-3.5 and reconstructed neutral pions at η~+3.5

Diiet Mass in Cu+Au at $\sqrt{s_{NN}}$=200 GeV



Dijet mass [assuming zero mass jets] for away-side azimuthal correlation peak

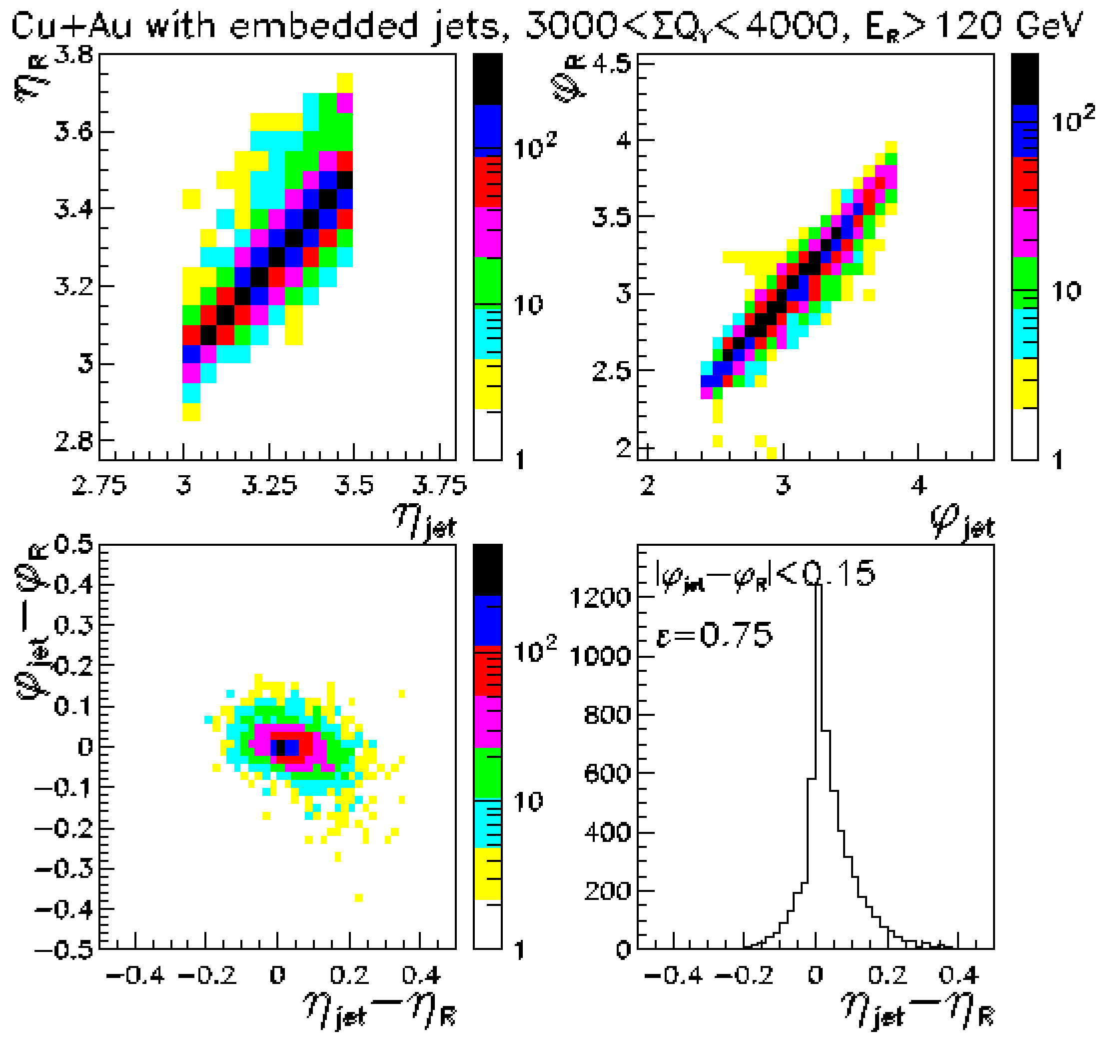


Dijet mass [assuming zero mass jets] for near-side azimuthal correlation peak

Observe a 5σ peak. Systematic studies still underway. Could this be a new particle?

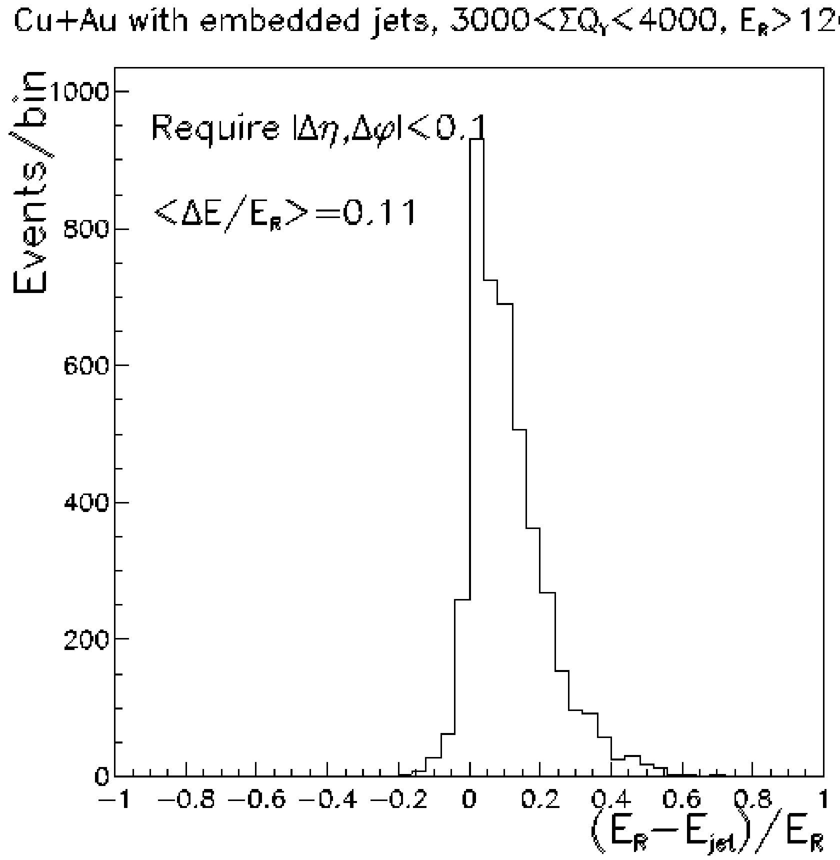
Are These Really Jets?

- Embed detector response from jets from p+p at √s=510 GeVwith E_{jet}>120 GeV into minimum-bias CuAu events
- Reconstruct result events, and compare to input jets
- Effects are smaller when including peripheral collisions



Jet directions match input jet

Jet energies shifted higher than input jet



Summary
Prospects for Low-x Physics at RHIC

- Improved forward instrumentation can extend experimental capabilities to allow measurements to $x \sim 10^{-3}$ in p+p collisions at RHIC

- A prime example of applicability is to extend gluon polarization measurements at RHIC to low x

- Low-x physics with heavy-ion beams provides sensitivity to large gluon densities, and helps establish their role in forming a quark-gluon plasma

- Forward detector upgrades also give prospects for discovery physics